



Environment
Canada

Environnement
Canada

Atmospheric
Environment
Service

Service
de l'environnement
atmosphérique

Earth Sciences Library

CA 1 EP2586172



THE STATUS OF RADIATIVELY ACTIVE GASES (RAGS): Measuring the Greenhouse Effect



Report on a Meeting Held at the
Atmospheric Environment Service
Environment Canada
15-19 September 1986

ARD-87-2

W.F.J. Evans A.J. Forester D.I. Wardle

Canada

Internal Report ARD-87-2

Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, Canada
M3H 5T4

PHOTOGRAPHS

FRONT COVER

Radiometers at the
Asquith, Saskatchewan
RAGS site, February 1987
-Lewis Poulin

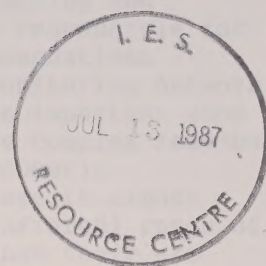
BACK COVER

Night launch of AES
Stratoprobe Balloon Payload
from Saskatoon, Saskatchewan,
February 1987
- Lewis Poulin

*Compliments of
Andrew Forster*

THE STATUS OF RADIATIVELY ACTIVE GASES (RAGS):

Measuring The Greenhouse Effect



**Report On A Meeting Held At The
Atmospheric Environment Service**

Environment Canada

15-19 September

1986

**AES
Internal
Report
ARD-87-2**

**Prepared By:
W. F. J. Evans
A. J. Forester
D. I. Wardle**

Digitized by the Internet Archive
in 2025 with funding from
University of Toronto

<https://archive.org/details/31761056882418>

EXECUTIVE SUMMARY

This report on the Toronto workshop has been prepared with the intention of stimulating discussion on how the international scientific community might organise to measure what may be a major perturbation to the global climate.

A plausible scenario suggests the concentrations of greenhouse gases in the atmosphere will continue to increase, and with them the net infrared radiation flux to the earth's surface. Ultimately, there may be a global climatic warming, perhaps with unprecedented environmental, socio-economic, and political implications. The warming will be delayed by some thirty to fifty years because of the thermal inertia of the oceans, which suggests that by monitoring the radiation changes, it may be possible to get an advance warning of this climate response.

The report assesses the feasibility of detecting and subsequently monitoring the radiative changes responsible for driving the climate perturbation, makes recommendations concerning the general specifications for a monitoring network and how they may be implemented and identifies important gaps in our knowledge of the problem (for example, the complex feed-backs exerted by water vapour and changes in cloud cover).

Thermally emitted radiation in the atmosphere is almost completely confined to the 5-35 micrometre (infrared) range of the electromagnetic spectrum. Within this range there are transparent and partially transparent regions - the so-called windows. Radiation measurements taken in the transparent (window) and partially opaque (edges of the window) regions are important for a comprehensive understanding of the greenhouse problem. Differing techniques may be required to study the windows and edges of the windows. It is necessary to measure: 1. spectrally resolved atmospheric emissions near the ground; 2. vertical profiles of the spectrally resolved radiation throughout the troposphere and up through the tropopause and 3. upward fluxes observed from a polar orbiting satellite. The results should be correlated with those from other programmes whose data relate to the greenhouse problem, with a broad-based set of ancillary atmospheric and climatological data, with the results from direct sampling and chemical analysis of greenhouse constituents and with other basic atmospheric data.

General circulation models (GCMs) are essential to an understanding of mechanism of the greenhouse effect, but they will be of limited use until their outputs can be validated against empirical radiation data. Model validation is one of the primary objectives of the network proposed here.

Between six and twelve monitoring stations should be established at high-, mid- and low-latitudes in both hemispheres. The selection of sites and the variables to be measured will require a careful evaluation of the current state of instrument technology, the results from a dedicated modelling exercise designed to optimize the performance of the network and careful consideration of those facilities now in operation.

Recommendations are made concerning the measurements of principal importance and a hierarchical strategy is suggested for deploying instruments according to their utility, availability and cost. The network should be dedicated to the primary objective of monitoring the greenhouse problem, and should not be compromised by other operational or scientific considerations. Long-term operation, quality control, reproducibility and comparability of data should be ensured. Extraordinary efforts to monitor instrument performance (e.g., maintenance of calibration) will be required.

SOMMAIRE

Ce rapport, tout en résumant une session de travail à Toronto, a été préparé avec l'intention de stimuler des discussions dans la communauté scientifique internationale qui encourageront l'établissement d'un réseau d'observation capable de mesurer ce que pourrait occasionner une perturbation majeure du climat terrestre, l'effet de serre.

Un scénario possible indique que la concentration des gaz importants à l'effet de serre va continuer à augmenter. Il en suivra une augmentation du flux énergétique net des rayons infrarouges dirigés vers la surface de la terre. Finalement on pourrait observer un réchauffement climatique global avec, possiblement, des impacts sans précédents sur nos environnements politiques, économiques et biologiques. La grande capacité thermique des océans devrait retarder de trente à cinquante ans l'apparition de ce réchauffement. Il est donc possible qu'en surveillant les changements dans le rayonnement nous puissions obtenir un indice d'ajustements climatiques futurs.

L'objectif de ce rapport est d'évaluer la possibilité de détecter et, par la suite surveiller, les changements dans le rayonnement atmosphérique qui sont responsables des pulsations climatiques. De même il fait des recommandations concernant des critères généraux pertinent à un réseau de surveillance et leurs intégrations subséquentes. Finalement, ce rapport identifie des domaines importants sur ce sujet requérant une étude continue pour une compréhension plus complète par exemple les rétroactions radiatives complexes des nuages et de la vapeur d'eau.

Les émissions thermiques infrarouges de l'atmosphère se situent principalement dans la section de 5-35 micromètre du spectre électromagnétique. Dans cette section du spectre nous retrouvons des régions transparentes et partiellement transparentes à ces rayons, ce qu'on appelle des fenêtres de transmission. Ce sont les mesures de rayonnement, prises dans ces fenêtres et dans leurs régions voisines, qui sont importantes pour une compréhension plus complète du problème de l'effet de serre. Différentes techniques seront probablement requises pour mesurer ces deux régions particulières. Il faudra mesurer: 1. les émissions spectrales atmosphériques près de la surface terrestre, 2. les émissions spectrales atmosphériques dans la troposphère et très basse stratosphère à l'aide de sondages en altitude, et 3. les flux de rayonnement dirigés vers l'espace observé d'un satellite avec orbite circumpolaire. Les résultats devront être corrélés avec ceux des autres programmes qui étudient aussi l'effet de serre, de même qu'avec la vaste quantité de données atmosphériques et climatologiques auxiliaires, avec les résultats des sondages qui mesurent directement la concentration des gaz reliés à l'effet de serre et finalement, avec les données météorologiques de base disponibles.

Des modèles de circulation générale sont essentiels à une compréhension du mécanisme de l'effet de serre mais leur potentiel ne sera pas exploité avant qu'on puisse comparer leurs résultats avec une multitude d'observations du rayonnement atmosphérique.

De six à douze stations de mesure devront être établies à de hautes, moyenne et basses latitudes dans les deux hémisphères. La sélection des sites et les variables à mesurer devront être évaluées en fonction des instruments présentement disponibles, des résultats de modélisations numériques qui viseront à maximiser les données du réseau et, tout ceci relié avec les programmes déjà en marche.

Des recommandations sont suggérées concernant les mesures les plus importantes. Une stratégie est aussi suggérée pour le déploiement des instruments en fonction de leurs utilité, disponibilité et coût. L'objectif unique du réseau serait d'acquérir des données utiles à l'étude de l'effet de serre. On devra s'assurer d'une opération à long-terme du réseau, d'une qualité acceptable des données et d'une vérification et comparaison adéquates de celles-ci. Ces critères engendreront des efforts particuliers pour surveiller les instruments et assurer un fonctionnement et étalonnage adéquats à tout moment.

CONTENTS

PREFACE	vii
ACKNOWLEDGEMENTS	viii
1. BACKGROUND	1
2. WORKSHOP OBJECTIVES	1
3. INTRODUCTION	2
4. THE ATMOSPHERIC EMISSION SPECTRUM NEAR THE EARTH'S SURFACE AND THE GREENHOUSE EFFECT	2
5. TESTING MODELS WITH RADIATION DATA	4
6. INFRARED EMISSION MEASURED FROM THE GROUND	5
7. INFRARED TRANSMISSION MEASURED FROM THE GROUND	6
8. PROFILING THE TROPOSPHERE	6
9. SATELLITE INSTRUMENTS	7
10. AN OBSERVATORY NETWORK	9
11. MAJOR UNCERTAINTIES: WATER VAPOUR AND CLOUD FEEDBACK	11
12. RECOMMENDATIONS	11
13. CHAIRMAN'S ADDRESS & TECHNICAL PAPERS	15*
APPENDIX A. Terms of Reference	195
APPENDIX B. Meeting Agenda	196
APPENDIX C. Contributors and Participants	199
APPENDIX D. Abbreviations and Acronyms	203
APPENDIX E. Glossary	207

* For list of presentations and papers see p.15

PREFACE

The greenhouse effect has, for good reason, received considerable attention in recent years because of its serious environmental, political and economic implications. Most of the scientific work has been in developing computer simulations which model the current state of the atmosphere and which give predictions of the climate change induced by increases in the concentrations of the greenhouse gases. The atmosphere has already been subjected to an increase in the greenhouse gases and some scientific studies have been undertaken to look for evidence of the resulting climate change in global temperature records.

Little attention has yet been given to measuring the changes in atmospheric radiation which cause enhancement of the greenhouse effect. Because of this the Atmospheric Environment Service convened a meeting of experts to consider how best to measure and ultimately monitor these radiation changes. The meeting was held in Toronto 15-19th September, 1986. The participants were specialists in infrared atmospheric technology, atmospheric radiation and climate modelling. Their deliberations are the basis of this report which attempts to evaluate the feasibility of detecting and monitoring the relevant changes in radiation and discusses the instrumentation and the strategy required.

This is a preliminary document intended to stimulate further studies and planning, which could lead to the establishment of a global capability for measuring the radiation changes associated with an enhanced greenhouse effect.

ACKNOWLEDGEMENTS

Environment Canada gratefully acknowledges the contributions of those who participated in the meeting and those who were unable to attend but who did provide technical papers and assisted by reviewing drafts of the report (Appendix C).

It is not always possible to develop a consensus when limited time is available for debating complex technical issues, and the reader should not think that those who contributed to the report are necessarily in complete agreement with all of the views expressed therein, or with all of its recommendations. The study was undertaken by the Research Directorate of The Atmospheric Environment Service of Environment Canada under the auspices of the World Meteorological Organisation (WMO). The Steering Committee comprising W.F.J.Evans and D.I.Wardle of the Experimental Studies Division and A.J.Forester of Dartside Consulting, was responsible for coordinating the meeting, and writing and editing the report. Many other members of the Division worked in support of the study, in particular Bruce MacArthur, Clive Midwinter and Lewis Poulin helped edit the report. Janet Young-Garner, Temporary Personnel Services, provided efficient and much appreciated text processing and general support during the study. Later drafts were composed by Gail Richardson, Force 8 Progressive Office Services.

A preliminary version of the report was presented by P.E.Merilees of the Atmospheric Environment Service to the Commission for Atmospheric Sciences of the World Meteorological Organisation at the Sofia meeting in 1986.

1. BACKGROUND

Solar radiation is partly attenuated in its passage through the atmosphere and about one half is absorbed by the ground. The energy is re-emitted as infrared radiation. This thermal emission is subsequently absorbed by gases in the atmosphere, and re-emitted downwards, raising the surface temperature 20 C above that expected from a theoretical atmosphere free of these gases.

This phenomenon is conventionally known as the greenhouse effect, and the gases responsible for it as greenhouse gases, or radiatively active gases (RAGs). Real greenhouses function by restricting convective heat losses, not by modifying the radiative regime within the enclosed space, but because the term "greenhouse" - and its derivatives (greenhouse effect, greenhouse gases etc.) - have entered current usage they are used in this report for convenience, noting this caveat concerning their literal inaccuracy.

The greenhouse effect is an essential part of the climatic system which maintains the surface temperature of the planet. In recent years it has become apparent that human activity has increased the concentration of greenhouse gases in the atmosphere to the extent that a small change in the radiation of the planet may have been detected. Much larger changes are anticipated in the future and a significant climatic warming may follow. Because of the large thermal inertia of the oceans, the climatic change may lag decades behind the radiation change. Given the global socio-economic impact that may be expected, it is prudent to try to monitor change in the radiative flux as soon as possible. Plans may then be made to control anthropogenic emissions of radiatively active gases, and adjust to the climatic changes it seems must follow if our present understanding of the climate system is valid.

2. WORKSHOP OBJECTIVES

The workshop was convened to -

- A. Decide if it is possible to detect, many years in advance of a climatic warming, the changes in radiation that may act as the driving force for that warming.
- B. Evaluate the possibility of making observations of radiation to test climate models, and the physical assumptions underlying them.

3. INTRODUCTION

The greenhouse gases include water vapour, carbon dioxide, methane, nitrous oxide, chlorinated fluorocarbons (especially CFC-11, CFC-12) and ozone, together with a large number of other trace gases that are either created by man, or whose atmospheric concentrations are modified by human activity.

Water vapour is an important greenhouse gas, an integral part of the normal atmosphere, centrally involved in radiation feedbacks and is an important factor in the response of the atmospheric system to radiative changes. As such, it must be studied along with, but in a separate fashion from, the other gases.

A monitoring system needs a long-term commitment of the type seldom approved by conventional funding sources. Such an endeavour must be jointly proposed, initiated and reviewed by the international scientific community for it to succeed. This document is intended to be a step in such a process.

4. THE ATMOSPHERIC EMISSION SPECTRUM NEAR THE EARTH'S SURFACE AND THE GREENHOUSE EFFECT

Most of the energy exchanged between the earth and the atmosphere by emitted radiation is in the wavelength interval 5-35 micrometres. Within this spectral range there are regions where the optical penetration is only a few centimetres, and others where the whole atmosphere may sometimes be almost transparent. These windows exist at 8-13 and 17-19 micrometres.

The response of the atmosphere to an increase in the concentration of any substance that enhances the absorption of radiation can be envisaged in two stages. First, there would be an increased atmospheric emission to the surface and less overall emission loss from the surface and the atmosphere to space. The upper troposphere would be heated the most, and atmospheric concentrations of water vapour would probably increase, causing an immediate positive feedback. More energy would be put into the surface and the low atmosphere, but the resulting temperature rise would be delayed because of the large thermal inertia of the oceans. Secondly, after several decades a new equilibrium would be established, with higher temperatures at the ground and in the lower atmosphere and with a correspondingly increased downward emission. The new atmosphere would also contain more water vapour and a changed cloud distribution. These changes exert major feedbacks which are poorly understood and so introduce a significant source of uncertainty into the prediction of climate.

The immediate response of the radiation field to changes in the concentrations of the RAGs is the driving force for the perturbation of the climate. Measuring the increased opacity of the atmosphere offers the potential for an early warning of impending climate change. The final response takes place over a wider range of the spectrum. It may be considerably larger but, over much of the spectrum, may be readily assessed by measuring the temperature of the air. If constituents continue to rise steadily, as has been happening in the past, the response of the whole system, being governed by the thermal inertia of the oceans, will be delayed, lagging behind the radiative forcing.

In spectral terms the atmospheric emission changes caused by alteration in opacity can be separated into three cases:

- A. In the spectral regions where the atmosphere is already opaque, changes in composition cause no alteration in emission. The emission is determined by the local temperature and the most accurate way to quantify it is to measure that temperature. Changes in the radiation in this region of the spectrum only occur as part of the delayed greenhouse response.
- B. In the spectral regions where the atmosphere is relatively transparent (the windows), increasing opacity has the potential for the maximum effect. The response is greatest if the absorber is in a cool region of the atmosphere. Monitoring the emission in this window could provide an early warning and identify the effects of unknown constituents.
- C. The calculation of radiation fluxes is complicated in the spectral regions where the atmosphere is partially opaque (edges of the windows). The problems of measuring spectral radiance at the window edges are different from those encountered in the windows. It is in these edges that the main driving force from carbon dioxide emission and the feedback from water vapour emission occur. To model greenhouse effects it is necessary to know how the effects of additional absorbers are masked by those already present.

There are important uncertainties in our knowledge of the line profiles and/or continua for both water and carbon dioxide, which are particularly important in and at the edges of the windows. Many atmospheric measurements with coincident temperature and humidity soundings are needed to validate model calculations.

Continued work on high-resolution measurements of absorption will also be needed. Low-resolution measurements can provide useful information on minor greenhouse constituents which are optically thin in the atmosphere.

5. TESTING MODELS WITH RADIATION DATA

Model verification is urgently needed. Spectral flux at the earth's surface is usually derived from first physical principles in radiation schemes. There is sufficient reason to believe that there may be discrepancies between the model outputs and the behaviour of the real atmosphere. Model predictions of radiative flux need to be rigorously tested against empirical data, especially to look for real effects that are not predicted by the models. The testing of radiation model outputs against real data sets is also important.

Measurements of upward and downward flux at the tropopause would provide a sensitive test because the changes anticipated at this level are large, about 1.5 Wm^{-2} downward from the stratosphere and -2.5 Wm^{-2} upward from the troposphere, for a net flux change of 4.0 Wm^{-2} . The corresponding surface change is only about 0.5 Wm^{-2} downward in the carbon dioxide bands. Models vary widely according to how the water continuum is treated so that surface measurements of the flux changes from water in the window regions are also very valuable. The predicted surface changes are about 15.0 Wm^{-2} . There will be a time delay between the direct carbon dioxide changes of 0.5 Wm^{-2} and the 15.0 Wm^{-2} response.

There are two mechanisms which increase the radiation at the surface: there will be an increased infrared flux at the tropopause which is propagated downwards by radiative transfer; there will be an increase in water vapour and with it the water continuum radiation. Additionally, the higher temperature in the upper troposphere will increase static stability and may reduce the upward transfer of latent and sensible heat, further enhancing the effect. There may be significant differences in the size of this effect between tropical and temperate latitudes.

These considerations suggest that profile measurements of radiation, temperature and humidity are essential. Balloon and aircraft measurements of the flux profile and particularly the net flux at the tropopause, would be extremely valuable and are absolutely necessary for comparison with the results of computer simulations.

To measure the greenhouse effect of radiatively active gases, the experimental results and model simulations should be compared under the same meteorological conditions, in a manner similar to that of the ICRCCM study. This will help to validate the radiation models and interpret the experimental results.

6. INFRARED EMISSION MEASURED FROM THE GROUND

There are two main greenhouse processes that affect the downward radiation fluxes at the surface: temperature rise, and the changes in spectral distribution caused by changes in atmospheric constituents.

The temperature rise is expected to be small, and may not be measurable within the time-scale envisaged for this monitoring scheme. Neither will the changed radiative fluxes be measurable in many of the spectral regions of the infrared because of the opacity of the atmosphere. Changes may be readily observed where the atmosphere is partly transparent.

The major window at 8-13 micrometres is determined by water and carbon dioxide, absorption at its lower and upper bounds, respectively. This window also lies near the peak of the atmospheric emission function, and therefore changes in this region will be especially significant. Many other greenhouse gases absorb and emit in the window so that studies of this spectral region can provide information on the effects of different constituents.

The 17-19 micrometre window which has significant energy and is controlled primarily by water vapour concentration, may consequently be important. The 4-5 micrometre window is not important because of the low energy in this region of the spectrum.

It is almost impossible to make and calibrate an instrument which measures spectral irradiance (spectrally resolved flux). However, spectral radiance, and spectrally integrated flux can and should be measured simultaneously with different instruments. Spectral radiance averaged over a field-of-view of about five degrees should be measured at a number of angles between the vertical and horizontal. These measurements can be integrated numerically to give the spectrally resolved flux (downward spectral irradiance). The dependence of radiance on the zenith angle also provides a critical test of radiation calculations. Spectrally integrated flux (non-spectral irradiance) is measured by currently available pyrgeometers. Continuing attention to calibration and characterization is needed to ensure the utility of these instruments.

Accurate calibration of instruments over long periods, is essential for detecting trends, and will be a major challenge. With good design, an accuracy of one per cent is possible, but it will be difficult to improve substantially upon this figure. The more accurate the measurements, the easier it will be to interpret them, particularly if pressure, temperature and humidity profiles, cloudiness and other standard meteorological parameters are measured simultaneously.

7. INFRARED TRANSMISSION MEASURED FROM THE GROUND

Most of the greenhouse gases can be measured from the ground by their effect on the solar spectrum in the 3-13 micrometre region. Climate changes should be correlated with long-term observations on the temporal and spatial distributions both of the atmospheric transmission and the concentrations of these gases (carbon dioxide, nitrous oxide, methane, ozone, nitric acid and CFCs). These measurements are best made by a network of dedicated stations working in conjunction with existing monitoring (e.g., ADN, GMCC, satellites, etc.) and modelling programmes.

Calibrations and inter-comparisons must be undertaken between all instruments used in the network, either by the use of travelling standards, or satellite observations to determine whether detected trends are global, small-scale, or spurious.

High-resolution, sun-pointing interferometers should be used to measure the transmission spectrum. Synthetic emission spectra can be derived from the transmission spectra and profiles of temperature and constituent concentrations. Investigation of these spectra in relation to measured spectra can be expected to improve the accuracy of radiation calculations.

The vertical column of all the greenhouse gases can be measured from the ground using sun-pointing spectrometers, and/or interferometers if the atmosphere is dry (<5 mm precipitable water) and the measurements are of high resolution ($<0.2 \text{ cm}^{-1}$). This is not the best method of measuring those greenhouse gases which are well-mixed in the troposphere (carbon dioxide, methane, nitrous oxide, CFCs) which should be sampled directly and chemically analyzed. Programmes exist to do this, although measurements of methane may not be sufficiently comprehensive to properly identify the sources.

Solar absorption spectrometers are most useful for measuring ozone and nitric acid in the stratosphere. Many other constituents which are important in the chemistry of the stratosphere, can also be measured spectrometrically, although high resolution is needed for many of these (e.g. 0.01 cm^{-1} for nitrogen oxide).

8. PROFILING THE TROPOSPHERE

Significant changes are predicted at all levels in the troposphere, especially at the tropopause. The vertical profiles of upward and downward fluxes are therefore needed because these provide a test of radiative transfer processes throughout the troposphere, particularly in the semi-opaque regions of the

infrared spectrum. Profiles can also provide information on the vertical distribution of greenhouse gases.

For correct interpretation, ground-based measurements must be complemented by information on the overlying atmosphere. Altitude profiles of trace gases (water vapour, ozone, methane, CFMs, nitrous oxide and nitric acid, in addition to aerosols and temperature) must also be monitored. At present, these measurements are most accurately obtained using instruments on balloons and aircraft in the lower atmosphere.

9. SATELLITE INSTRUMENTS

To confirm the accuracy of model predictions of radiative fluxes in the atmosphere, the spectrum of both the upward and downward fluxes must be measured. Similar instruments should be deployed at ground stations, on balloons and aircraft, and on a satellite. Because of the long lead time before instruments can be placed on satellites, development should begin soon. The instruments' absolute accuracy, spectral resolution and field-of-view should be similar to those of the ground-based instruments.

A polar-orbiting satellite is needed to achieve global coverage and the instrument should resolve several discrete angles between nadir and the limb. Although the temperature uniformity within such an instrument is more difficult to maintain on a satellite than on the ground, other aspects of radiometric calibration are superior: the measurement of zero is better (by viewing space just above the limb of the atmosphere) and temperature gradients across the black body used for calibration can be made smaller. It will be difficult, but important, to confirm the long-term accuracy of the calibration of this instrument. A similar exercise has been successful for the temperature sounding radiometers on the NOAA satellites. High priority should be given to the development of an instrument for measuring changes in the spectrum of upward flux. Other existing and proposed satellite-borne instruments and research programmes of importance include:

- A. The ERBE which measures the total short-wave fluxes of sunlight reflected by clouds, and the earth's surface. This provides an important input to climate models.

- B. The ERBE also measures the total upward long-wave flux. It may be difficult to distinguish the small forcing changes in flux, caused by changes in carbon dioxide, from other variables. The ERBE monitor should permit cloud effects and clear sky radiation to be separated, enabling the cloud radiative forcing to be quantified. This may require enhancement of the temporal and spatial resolution of the instrument. After a climatic response to a step change in forcing, the net global upward flux must return to its previous value. The redistribution between the short- and long-wave can be measured and monitored by the ERBE.
- C. Unlike ground-based instruments, satellite-mounted sensors measuring flux in the 11 micrometre window with low spectral resolution (e.g. METEOSAT, AVHRR) provide very little information about greenhouse emissions from nitric acid or CFCs. This is because their signals are masked by varying emission from the earth's surface and low troposphere. A high-resolution, space-based instrument, resolving better than 0.5 cm^{-1} on the upward radiance at 11 micrometres, would identify the nitric acid and CFC signatures above the water vapour and surface background.

Except for carbon dioxide, those greenhouse gases which are well-mixed in the troposphere (e.g., methane, nitrous oxide, CFMs) are best measured by gas chromatographic analyses of tropospheric samples. They cannot normally be measured in the troposphere from satellites and the small parts of their vertical columns which reside in the stratosphere are not important. Measurements of their profiles from satellites, though important for stratospheric chemistry, are less useful for measuring the greenhouse effect.

The stratospheric greenhouse gases (ozone and nitric acid) should be measured by stable instruments which maintain their calibration over long periods. This can only be guaranteed by a network of ground stations. Satellite measurements must be used to check how globally representative such data are. Ozone should be monitored from satellites in stratospheric chemistry research programmes. For calculations of the greenhouse effect of nitric acid, it may be sufficient to measure its stratospheric column from the ground, with occasional aircraft flights to confirm that the samples are representative. A limb-scanning filter radiometer, with comparatively coarse vertical resolution (5 km) to measure nitric acid from a satellite would be useful.

The carbon dioxide above 40 km is important in the radiation balance of the stratosphere. Its concentration there can be monitored by solar absorption spectrometers on satellites (e.g. ATMOS), although the accuracy is poor compared with that of chemical analysis of tropospheric samples. However, no mechanism

has been proposed whereby the carbon dioxide above 40 km might change independently of the changes in its tropospheric concentration.

10. AN OBSERVATORY NETWORK

A long-term programme extending over some decades would be necessary to monitor a change in radiation sufficient to effect an alteration in climate. Although a ten-year programme may show trends, a longer operational period would be needed to ensure that significant effects caused by changing concentrations of greenhouse gases are not confused with natural variations. The main requirements for a network are:

- A. Sites must be located so that global effects can be differentiated from local perturbations. This will require between six and twelve ground-based monitoring sites, distributed as widely as possible with respect to latitude and climate zones.
- B. Good conditions for measurement of the main parameters of interest.
- C. Ancillary variables should be measured to: compile a database of broad utility in assessing climatic change, undertaking quality control on the network's performance, and to assist in reducing ambiguities concerning the size and causes of any changes that may be detected.
- D. Provision should be made to ensure that comparable data can be collected continuously over a long period.
- E. The instrumentation and observational procedures should be designed so that an identical, or equivalent, measurement system can be reproduced in the future.
- F. Measurements should be of sufficient frequency, duration and extent that trend analysis produces meaningful results.
- G. The siting of stations in the network and selection of variables to be measured should be guided by a specialised simulation modelling effort. The overall design must be a synthesis of the results of this modelling effort with current knowledge of measurement technology.

There should be a variety of instruments, measuring different variables classified according to priority:

Class 1.

These instruments (e.g., pyrgeometers and simple spectral radiometers and spectrometers) would be present at each site. They require a clear sky, low turbidity and low water vapour for their effective operation. The objective is to measure radiative forcing not the feedback, climatic response. These instruments, which should be exceptionally reliable and stable, measure:

- A. Spectrally integrated downward flux
- B. Spectrally resolved zenith radiance
- C. Temperature, pressure and humidity profiles
- D. Atmospheric transmission by solar absorption

Class 2.

The instruments in this category are appropriate to methods and techniques for which less confidence and experience exists. Most have operational histories of less than five years, with limited data for intercomparison. Examples include lidar (temperature, pressure and ozone), and solar absorption interferometers (atmospheric transmission).

Class 3.

This includes new techniques and prototypes (e.g., high resolution interferometers and ultra-high resolution heterodyne spectrometers). The design and development of new sensors should take every possible advantage of data acquired from the long-term operation of earlier instruments. New instruments should be introduced at sites where extensive monitoring is already in progress.

The network should be flexible enough to contribute to other research programmes, and specific research needs as they inevitably arise. These considerations should not interfere with the main purpose of the network, whose basic instrumentation, data collection, and operational protocols should be conserved.

Given that the greenhouse effect appears to vary greatly with latitude, it follows that sites should be distributed as widely as possible over high and low latitudes, in both northern and southern hemispheres. Siting considerations should incorporate input from the specialized simulations, and the current state of instrument technology, to optimize the performance of the network.

11. MAJOR UNCERTAINTIES: WATER VAPOUR AND CLOUD FEEDBACK

Water vapour and cloud feedback introduce major uncertainties into an understanding of the greenhouse problem. Water vapour is a primary contributor to the spectral opacity of the atmosphere, and is therefore a radiatively active gas. It also affects the planetary albedo. For these reasons, water vapour has the potential to generate either positive feedbacks (by increasing infrared absorption), or negative feedbacks (by contributing to increased cloudiness). The understanding of water vapour in general and global cloud distribution in particular, needs to be developed further. The ISCCP is addressing the cloud-feedback problem directly. The behaviour of the continuum radiation from the water vapour represents a major uncertainty in greenhouse studies, both in the model radiation codes, and as a source of interference in detecting changes in radiation from other greenhouse gases.

12. RECOMMENDATIONS

General Considerations

Recognizing that:

1. Modification of the atmosphere, with a potential for climatic change, is a direct consequence of human activity (energy policy, use of CFCs, etc.) and should be recognized as such.
2. The coupling between human activity and climate change is beyond question (and not invalidated by the many gaps in our understanding of the problem and how to manage it).
3. Man-made emissions of greenhouse gases to the atmosphere have long-term socio-economic and political implications; control strategies have both short- and long-term socio-economic impacts.
4. An increase in concentration of greenhouse gases is believed to be an agent for climatic change through their effects on the opacity of the atmosphere.

5. The thermal inertia of the oceans may mask inevitable climate change with a 20-50 year time lag, making it imperative that an early-warning signal, in the form of changed radiative fluxes, be looked for in advance of a measurable temperature change.

There is a need to:

1. Establish a monitoring network for downward atmospheric emission working in conjunction with: (a) satellite observations on the outgoing long-wave flux with some spectral resolution and (b) a continuing effort in simulation modelling.
2. Verify the radiative transfer and radiation calculations used in the study of climate change.
3. Undertake a specialized study in simulation modelling to use for network design.
4. Monitor the long-term changes in the transmission of the atmosphere.

Specific Recommendations Concerning The Network

1. Long-wave radiation is the subject of these recommendations, but it is recognised that short-wave radiation and the influence of clouds are of similar importance in determining the climate. Complementary studies on both the longwave and shortwave radiation should be planned.
2. The network should concentrate on radiative fluxes and the spectral data should be correlated with chemical analyses of samples of those greenhouse gases (e.g., carbon dioxide, methane, nitrous oxide, nitric acid, CFCs) that are well-mixed in the troposphere.
3. A network of approximately six to twelve stations should be sited with respect to latitude and climatic zones so that global effects can be unambiguously differentiated from smaller scale phenomena.

4. The 8-13 micrometre window is the most important with respect to the downward fluxes. Window opacity and the downward fluxes should be studied in relation to the gases identified above, other trace gases and aerosols and to temperature.
5. The large radiance changes induced by carbon dioxide and water occur at the edges of the windows, and the spectral radiance must be monitored here, as well as in the windows. There are special measurement problems caused by the large wavelength gradient of radiance, and care is needed to solve these.
6. The angular variability of spectral radiance is a sensitive test of radiation calculations. Spectral irradiance data should be obtained by numerical integration of radiance measurements taken over a range of zenith angles.
7. Spectral radiance should be measured on the ground and at the tropopause because models are most sensitive to verification at these levels.
8. The long lead-time required for putting instruments on satellites precludes their immediate use. There are apparently no firm plans for measuring spectral radiance from satellites and serious consideration should be given to developing such a programme.
9. It is important both to have simple and reliable equipment in long-running operation at several stations and to deploy more advanced equipment when it becomes available. A hierarchical strategy for deploying instruments is discussed in the report.
10. Emission measurements will require greater attention to calibration and characterization of the instruments than has been customary. Instrument characteristics must be monitored and documented as a continuing process. Portable instruments would be useful, both for checking on calibration and characterization at different sites, for acquiring limited data at special locations and to get a reliably calibrated, low-cost network operational with minimal delay.
11. The network should be periodically reviewed with respect to the calibration of its instruments and to assure that its operation serves the needs of the scientific community, without departing from its stated objectives.

12. Monitoring and research should not be considered separate domains and the research community should be involved in an assessment of the network's operation to ensure that its needs are met and that new instruments are introduced when and where appropriate.
13. The network should be implemented in stages. The complement of instruments could be progressively increased as funds and new sensors become available and as an understanding of the greenhouse problem becomes clearer. It is stressed in the report that any changes must only be in the form of adding new instruments, not by the replacement of existing sensors, even when these are no longer the most advanced that are available.
14. The network should include proven observatories, e.g. Mauna Loa and Haute-Provence so that greenhouse radiation data can be complemented by a comprehensive set of ancillary climate records. An attempt should be made to coordinate the greenhouse network with the proposed NASA Stratospheric Change Observatory Network.

13. CHAIRMAN'S ADDRESS AND TECHNICAL PAPERS

List

Chairman's Address

P.E.Merilees. Radiatively Active Gases (RAGS) and the Climate Problem	17
--	----

Technical Papers

G.J.Boer. General Circulation Models	21
H.Buijs. Fourier Transform of Infrared (FTIR) Interferometry	25
Requirements for a Radiative Transfer Observatory	35
M.T.Coffey & W.G.Mankin. Atmospheric Transmission Measurements Using Ground Based Infrared Fourier Transform Spectroscopy	39
J.J.DeLuisi Aerosols, Water Vapour, and Cloudiness at the Mauna Loa Observatory, and the South Pole	47
J.Drummond. The GENLIN Radiation Programme	55
A.Dudhia. Inter-Calibration of METEOSAT and AVHRR	65
W.F.J.Evans. Measurement of the Greenhouse Effect of Chlorofluorocarbon-11 (CFC-11)	75
Proposal for a Radiatively Active Gas (RAGS) Observatory	81
J.C.Gille. Infrared Limb Sounding of the Middle Atmosphere	85

D.W.Johnson & G.M.Stokes. A Ground-Based Network of Trace Gas Monitoring Instruments Using Medium Resolution Fourier Transform Spectrometry	91
P.Marché. Umkehr Observation of the Ozone Layer, and Infrared Measurements of Stratospheric and Tropospheric Minor Constituents	101
A Fourier Transform Spectrometer	117
D.G.Murcray. Comparisons of Observed and Calculated Spectra	119
R.W.Nicholls. Realistic Syntheses of Atmospheric Extinction Spectra	133
H.Roscoe. The Stratospheric and Meso- spheric Sounder (SAMS) Plots	143
R.K.R.Vupputuri. Potential Effects of Anthropogenic Ozone, Temperature Structure and Surface Climate	147
D.I.Wardle. The Canadian Radiation Network and Long-Term Records of Pyranometer Calibration 1960-1984	157
D.I.Wardle & L.J.B McArthur. Ground Level Monitoring of Long-Wave Irradiance with the Eppley Pyrgeometer	173

CHAIRMAN'S ADDRESS

Radiatively Active Gases (RAGS) And The Climate Problem

P.E. Merilees

Atmospheric Environment Service
Environment Canada

INTRODUCTION

The question of changes in the composition of the atmosphere in the form of increases in radiatively active gases, and the resulting potential for climate change is surely one of the most important scientific questions facing atmospheric scientists.

That carbon dioxide has increased substantially over the past 30 years is indisputable. Whether it will continue to increase, and what it means for the earth's climate, is much more open to scientific discussion.

In addition, it has been more forcefully recognized in the past few years that carbon dioxide is only one of many trace gases which are on the rise and which actively absorb in the infrared. The scientific community has come to call this collection of gases RAGs. Some are clearly man made (e.g., CFCs), and are of concern in the context of the ozone layer. Others are part of a natural cycle (e.g., methane) and for these it is much less obvious why they are increasing in the atmosphere. Realization that other RAGs (i.e. apart from carbon dioxide) have the potential to accelerate the process of "dirtying" the atmospheric window has led to a renewed vigour to address the questions.

Getting better knowledge about RAGs, and the climate changes that they may cause, is obviously very important from both the scientific and socio-economic points of view. If indeed, the changes in the levels of RAGs will lead to significant climate change, then we need to know what they are likely to be, even if we have no way of affecting the eventual outcome. Indeed, it is likely that there will not be a general agreement that all such changes are bad.

There is another important reason to strengthen our knowledge and understanding of these questions. In my view, energy futures and policies will be on the political agenda for as long as I'm around. The recent accident at Chernobyl has renewed the debate about nuclear energy. The discussions and decisions on the future and effects of various energy sources will, without doubt, involve questions of climate change.

It may seem strange to talk about this "blip" in public attention in a meeting which is formulating a proposal for a long series of measurements. I submit however, that the debate and decision making will continue for many decades, varying only in intensity depending on events and scientific knowledge.

As such, we must equip ourselves with the best information and knowledge so as to provide the best scientific advice on these issues.

A SIMPLIFIED DESCRIPTION OF THE CLIMATE CHANGE DUE TO RAGS

At present moment, we reason that increasing the concentration of RAGS in the troposphere will lead to a "dirtying" of the atmospheric window. In the absence of a compensating change in the net solar energy received by the earth, the effective height of the long-wave return of energy must rise, and therefore the temperature of the atmosphere at the new height must increase. Because the troposphere is convective, it must undergo a general rise in temperature. Such is a global view.

However, since the distribution of incoming solar radiation is dependent on latitude (among other things), the balance of incoming and outgoing radiation will not be uniform. Because this non-uniformity is the essential driving mechanism for the circulation of the air and water, changes must surely change how the circulation takes place and thus the climate on a regional basis as well.

It seems clear that one cannot expect the response of the climate system to changes in radiation to be either straightforward, or immediate. First, there is the considerable thermal inertia generated by the oceans and ice which will slow the temperature response with a characteristic time lag of perhaps 20-40 years. Second, there is the role of water vapour as an important radiatively active gas, and the question of how its distribution will respond to a changing radiation regime. Finally, there is the possibility that the climate can respond to a change in the concentration of RAGs in other more subtle ways, perhaps by establishing a new equilibrium through changes in cloudiness.

THE CASE FOR MEASURING RAGS

The likelihood of a delayed response to changes in RAGS implies that one has the possibility of detecting an impending change. At the same time, for the same reason, it also implies that there may be little that could be done about it once such a point is reached.

At present, there are some scientists who believe that examination of the climate record over the past century indicates a general warming of the sort that might be expected from increases in carbon dioxide. In my view, the case is not particularly strong. I would feel more confident if there were hard evidence of changes in the radiation balance. This is of course a fundamental difficulty in geophysics: that we cannot go back and take these measurements, but now wish we had done so.

For these basic reasons, it seems to me that we must examine the question of long-term, stable measurement of the long-wave and short-wave regimes at a number of high-quality observatories around the world. These measurements must be augmented by independent measurements of the composition of the atmosphere, and coupled through our knowledge of radiative transfer. It seems to me that one cannot concentrate solely on the long-wave regime because the climate system will just not hold still for us to see what would happen with increasing concentrations of RAGS alone.

Our ability to model the climate system will be crucial both to understand what has happened, and to predict what will happen. As such, the strengthening of observational programs to test and verify model calculations of radiative transfer will be an important step.

FINAL REMARKS

The prospect of climate change due to increasing concentrations of RAGS demands that we institute long term measurement programs to provide hard evidence that our theories are sound and our understanding of the problem is solid. It seems to me that direct measurements of the greenhouse effect could play a key role in this process of nailing down the inferential chain. In addition, it is possible that such measurements could provide a method of early detection of impending climate change.

General Circulation Models

George J. Boer

**Atmospheric Environment Service
Environment Canada**

The following notes represent a synopsis of Dr Boer's presentation to the meeting.

RADIATIVELY ACTIVE GASES AND GENERAL CIRCULATION MODELS

The Problem the detection and prediction of climatic effects of RAGS

GCMS Used to translate specific physical change (ie. concentrations of RAGs) into climatic response

Climate Response A 3-D change in basic climate parameters (temperature, precipitation, wind etc.) caused by change in the system

CLIMATE MODELLING

The Climate System Is Complex

Global in extent
Atmosphere, oceans, cryosphere, biosphere
Many scales that interact

The Climate System Is Non-Linear

Small changes may cause large responses, or vice versa
Dangerous to extrapolate

Controlled Experiments Not Possible

Unlike lab. sciences, only uncontrolled experiments possible, e.g:

1. Natural (volcanos, ENSO, solar variations)
2. Man-made (surface changes, carbon dioxide, other pollutants)

THE CLIMATE IS A PHYSICAL SYSTEM

1. The normal laws of physics hold
2. The problem is to make realistic approximations and solve the resulting equations

This leads to **Climate Models**

1. Reproduce climate from First Principles
2. Enables modelling experiments
3. Possibility of climate prediction

GENERAL CIRCULATION MODELLING

1. Reproduces observed climate from First Principles
2. First Principles (for climate):
 - A. Newton's 2nd law (momentum eqns.)
 - B. Conservation of mass (continuity & moisture eqns)
 - C. Conservation of Energy (thermodynamic eqn)
3. GCM embodies these principles and deduces global climate from external forcing terms
4. Solve numerically as a function of time
5. Model atmosphere should evolve in similar manner to real atmosphere
6. Model Wx maps should be like observed maps
7. The model climate follows as the long-term statistics of the solution (require a number of years of simulated time)

ROLE OF GCMS

Detection

Explain past forced climate variation

Finger Print, for past/present/future climatic effects

Prediction

Provide 3-D climatic effect given basic concentration and radiative properties of RAGs (etc.)

TYPICAL GCM

~10 levels in vertical (few, if any, in stratosphere)

5 x 5 degree grid, or equivalent

Perpetual to diurnal cycle for radiation

Fixed SSTs to 3-D coupled GCM

Troposphere orientation

STRENGTH OF GCMS

Climate from First Principles, i.e. reasonably complete physics and dynamics of the system

Information provided on geographical, vertical and temporal distribution of climate parameters

Exhibits natural variability similar to the physical system

WEAKNESSES OF GCMs

1. Costly
2. Parameterization-dependent
 - A. Radiation
 - a) Band calculation (spectral interval: IR 1~6, S-W 1~2)
 - b) Distribution of RAGs other than water is usually specified
 - c) Aerosol effects often absent
 - d) Very sensitive to cloud distribution and optical properties
 - B. Clouds
 - a) Parameterizations governing distribution and optical properties are critical
 - C. Boundary layer and surface budgets
 - D. Effects of orography
 - E. Resolution
 - F. Oceans & Ice
 - a) Critical, and difficult because of time & space scales of oceans
 - b) Ice dynamics, and thermodynamics for ice-albedo feedback
3. Systematic Errors
 - A. Many models have similar problems
 - a) Stratosphere
 - b) Surface pressure/wind

GCMs & SURFACE BASED RADIATION DATA

1. Model Development (-> GCM)
 - A. Improved radiation codes for GCMs?
 - B. Improved RAG distributions and radiative properties?
 - C. Inclusion of evolution eqns for RAGs?
2. Model Verification (-> GCMs)
 - A. Model radiation climatology verification?
 - a) Broad-band
 - b) Variability
 - c) Stratosphere problem
 - d) Clouds
3. Detection (<- GCM)
 - A. GCM fingerprint in conjunction with measurements?
 - B. Network design
4. Prediction
 - A. The job of a sufficiently good model

Fourier Transform of Infrared (FTIR) Interferometry

Henry Buijs

BOMEM Inc.

The following notes represent a synopsis of Dr Buijs presentation to the meeting and summarises the available instrumentation and its capability.

AVAILABLE INSTRUMENTATION

BOMEM INC.

Start up 1974: Early instrumentation.

AES balloon borne FTIR

Self aligning
Servo alignment

Unattended operation

0.1 cm^{-1} APOD RES 5 cm stroke

Solar spectroscopy to determine trace constituents

80 sec scan time
Dual detector
 $2.5 \text{ } \mu\text{m}$ HF + H_2O + CO_2
 $3.5 \text{ } \mu\text{m}$ HCl + CH_4 + NO_2

UNIVERSITY OF DENVER DA2 SERIES FTIR

Solar spectroscopy to determine trace constituents

Resolution to 0.02 cm^{-1} , 25 cm stroke
Hardwire numerical filtering
Leads to data compression without aliasing
790,000 to ~50,000/scan
40 sec scan time
LHe cooled detector 5-14 μm
High sensitivity
High selectivity

DREV (CORTEC) DA2 SERIES FTIR

Ground based field spectroscopy emission from rapidly changing targets: Aircraft, rockets stationary or in flight.

Very rapid scanning
0.1 cm^{-1} res 2 sec
10 scans/sec 1 cm^{-1} .
Real time spectra HSVP

numerical filtering
phase correction
data compression
Fourier transform

Large telescope
Video tracking

DREV (FIT) DA2 SERIES FTIR

Absolute long path transmission

Radiometrically calibrated

Source with 150 cm telescope
Receiver with 45 cm telescope
Interferometer I/O optics

Determine absolute transmission of 5 km air path

1-15 μm
0.04 cm^{-1} res
7% max error

Interest in

H₂O continuum
Detailed local T for laser transmission
Dependence on weather

NASA GODDARD DA2 SERIES FTIR

Upper atmosphere minor constituent by emission

Liquid N₂ cooled interferometer limb scanning

4 detectors with medium/narrow band cold filters for specific spectral regions

1 detector broad band

Liquid He cooled detectors

ATMOS J.P.L. HONEYWELL SHUTTLE BORNE SOLAR FTIR

Very rapid scan

2 sec/scan

0.04 cm⁻¹ Apodised

Broad band data processing

Successful flight Spring 1985

Many sunsets

Many sunrises

Very complete spectra

Excellent S/N ratio

Excellent line shapes

Costly optics

Costly operation

UNIVERSITY OF WISCONSIN (HIS) DA2 SERIES FTIR

Upwelling emission observed from U2 aircraft

Radiometric calibration

Internal BB sources

Complex algebraic computation of calibration

3 detectors liquid He cooled.

Absolute determination of vertical temperature

Resolution 0.5 cm^{-1} capable

U. OF DENVER DA3 SERIES FTIR

Solar spectroscopy to determine minor constituents

Increased resolution to 0.004 cm^{-1} apodized

Balloon borne

Very high selectivity

High sensitivity

Large optics

UNIVERSITY OF OREGON FAR IR EMISSION FTIR

Very high resolution

Minor constituents atmosphere laboratory

BOMEM hardware/software

Support for in-house construction

0.002 cm^{-1} res apod.

$10\text{-}100 \text{ cm}^{-1}$

Narrow band cold filtered

Bolometer LHe³ temperature

NEP < 10^{-16}

Observe HCl, -OH, ClO

SBRC (TES) MARS MISSION THERMAL EMISSION SPECTROMETER FOR MARS ORBITER

SBRC-BOMEM joint project

Geological and atmospheric mapping of mars

$200 - 1600 \text{ cm}^{-1}$

10 cm^{-1} resolution

6 detectors DTGS & FOV

6-8 km IFON.

2 sec/scan

Full on board spectral processing

GENERAL CHARACTERISTICS DA2 SERIES FTIR.

- Self aligning
- Dynamic alignment
- Flat mirror Michelson
- Wide range of mirror velocities
- Wide range of resolution
- Precise line shapes
- Any orientation
- Vibration resistant
- Temperature resistant
- Evacuatable
- Wide spectral range

GENERAL CHARACTERISTICS DA3 SERIES

- High level of versatility
 - Range FIR, MIR, NIR, VIS, UV
 - Resolution 40-0.004 cm^{-1}
 - Multi-experiment
 - Transmission, emission
- Vacuum
- Immediate data processing
 - Co-adding
 - Numerical filtering
 - Phase correction
 - FT 10 sec 100K pts
- Complete processing software
- Very high S/N all resolutions and all detectors
- Very high precision of intensity
- High stability

NEW MICHELSON-100 SERIES

Philosophy of low cost

FTIR sensors with fixed characteristics but high performance

Family of devices

100 introduction Sept. 1986

400-5000 cm^{-1}

4 cm^{-1} resolution

DTGS optimized

S/N = 1000 SIG/PTOP noise 4 sec

Stability <0.1% dev 100% line

Linearity to 4A

Vibration insensitive dynamically balanced
scan mirror

Temperature range 5-40 C

Sealed

>10,000 hrs MTBF

Industrially hardened

Different models for different tasks

Spectral range FIR, NIR, VIS

Resolution models with 2 cm^{-1} , 1 cm^{-1} , 0.5 cm^{-1}

Scanning speed -> 50 scans/sec

4 port dual beam

Polarizing

Open software for adaption to different tasks

Correlation

Curve fitting

Quantitative analysis

Spectral subtraction

Library search

Basic sensor cost aprox. \$17,000 U.S.

Basic computer IBM-PC

CONCLUSIONS

FTIR instrumentation has reached a high level of maturity and its application is warranted when throughput and multiplex advantages are needed, and also for:

- Low cost
- Simplicity
- Small size
- Ruggedness
- Precision of measurement
- Reproducibility
- Ease of data handling
- Versatility

APPENDIX

BOMEN Michelson 100 Series FTIR

The FTIR signal to noise ratio is given by:

$$s/n = \frac{P_{\sigma} A \Omega \epsilon \sigma_{res} t^{1/2}}{NEP} \quad \frac{\text{signal}}{\text{rms noise}}$$

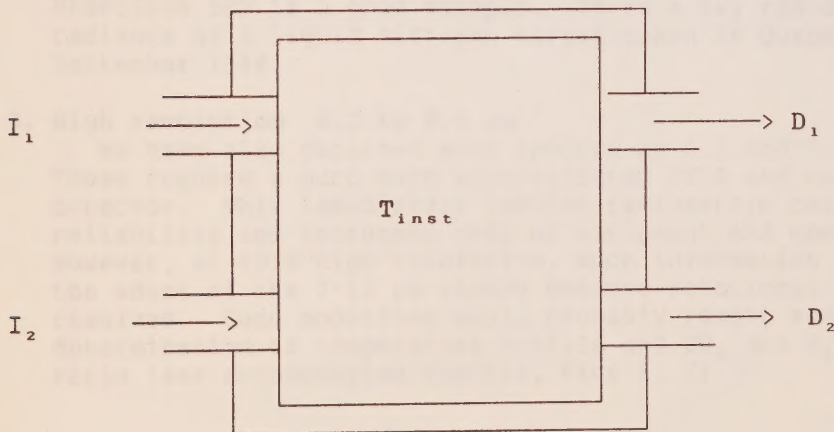
P_{σ}	=	incident power
A_d	=	0.04 cm^2
Ω_d	=	1 sterad
ϵ	=	0.05 transmission + modulation
σ_{res}	=	4 cm^{-1}
T_{res}	=	observation time
NEP	=	$5 \times 10^{-10} \text{ watt/}\sqrt{\text{Hz}}$

Detectable change $s/n > 6$ Assuming typical observation time = 400 sec 100 scans, the minimum detectable $\delta P_{\sigma} = 19 \times 10^{-9} \text{ watts/cm}^2 \text{ sterad (cm}^{-1}\text{)}$.

Black Body Radiation and Radiation Change

	P_{σ}	200K $\delta P/\delta T$	P_{σ}	250K $\delta P/\delta T$	P_{σ}	300K $\delta P/\delta T$
200 cm^{-1}	2.9 μW	27 μW	4.4	29	5.92	33
NE δT		0.7°		0.65°		0.58°
400 cm^{-1}	4.5	69	8.5	T5	13	99
		0.27°		0.25°		0.20°
800 cm^{-1}	1.9	57	6.1	116	13	180
		0.33°		0.16°		0.10°
1600 cm^{-1}	0.048	3	0.5	18	2.3	58
		6.3°		1.06°		0.33°

The objectives are to measure emission spectra in the upwards looking direction in the 400-1600 cm^{-1} (beyond 1600 cm^{-1} region is available, but probably too low signal). Temperature range in emission is 200 K to 310 K with varying emissivity. The basic Michelson 100 interferometer is a 4 port interferometer.



A detector at D_1 sees the difference spectrum of $I_2 - I_1$

- The precision of the difference $I_2 - I_1$ depends on constancy of temperature of spectrometer (spatial gradients)
- The dynamic range of the measured signal depends on matching I_2 to I_1

I_2 may have a black body of a convenient temperature to minimize dynamic range and calibration error. However, simplest scheme is to build I_2 reference inside instrument and maintain at T instrument (T instrument could be freezing water 0°C in a refrigerated box).

Data handling is summarised:

All data is collected and processed by IBM-PC type computers

One spectrum is represented by about 1000 data points

Assume about 250 bytes of data for housekeeping

Total ~ 2500 bytes

Scan time 400 sec 6.25 bytes/sec

Use write-once optical disc 1 gigabyte/platter good for ~40000 hrs of data logging.

Requirements for a Radiative Transfer Observatory

H. Buijs

BOMEM Inc.

It is very important in monitoring downward emission fluxes to have radiometric calibration, particularly in the 7-14 μm window. This cannot be emphasized enough.

However, having seen the measurements presented by Dr Evans (probably about 25-30 cm^{-1} resolution), and two ground-based measurements we undertook recently, it is apparent that there are 3 three resolution regimes to be considered.

1. Very Low Resolution Radiometry $>25 \text{ cm}^{-1}$

Obtain a coarse total radiance with very limited distinction of components, temperature distribution, and consequently height distribution.

2. Medium resolution 2 or 4 cm^{-1}

This is an important resolution because it already separates most components of the atmosphere, and yet these measurements can be achieved with very linear response, ambient temperature detectors, and a well controlled ambient temperature FTIR. The cost of the instrument and its operation would be very modest, and a good long-term reliability can be offered. It is believed that our 4 port Michelson interferometer could maintain good radiometric calibration over a long period of time: better than 0.1 K deviation over the 200-300 K measurement range. The spectrum HBSP27006.SUB is a good example. It is a sky radiance minus radiance of a liquid nitrogen target taken in Quebec 27th. September 1986.

3. High resolution 0.2 to 0.5 cm^{-1}

We have also obtained some spectra at 0.2 and 0.5 cm^{-1} . These require a much more sophisticated FTIR and cooled detector. This immediately reduces radiometric calibration reliability and increases cost of equipment and operation. However, at this high resolution, much information is added at the edges of the 7-14 μm window because rotational lines are resolved. Good modelling would probably permit some determination of temperature profile and CO_2 and H_2O mixing ratio (see accompanying spectra, Figs 1, 2).

FIGURE 1.

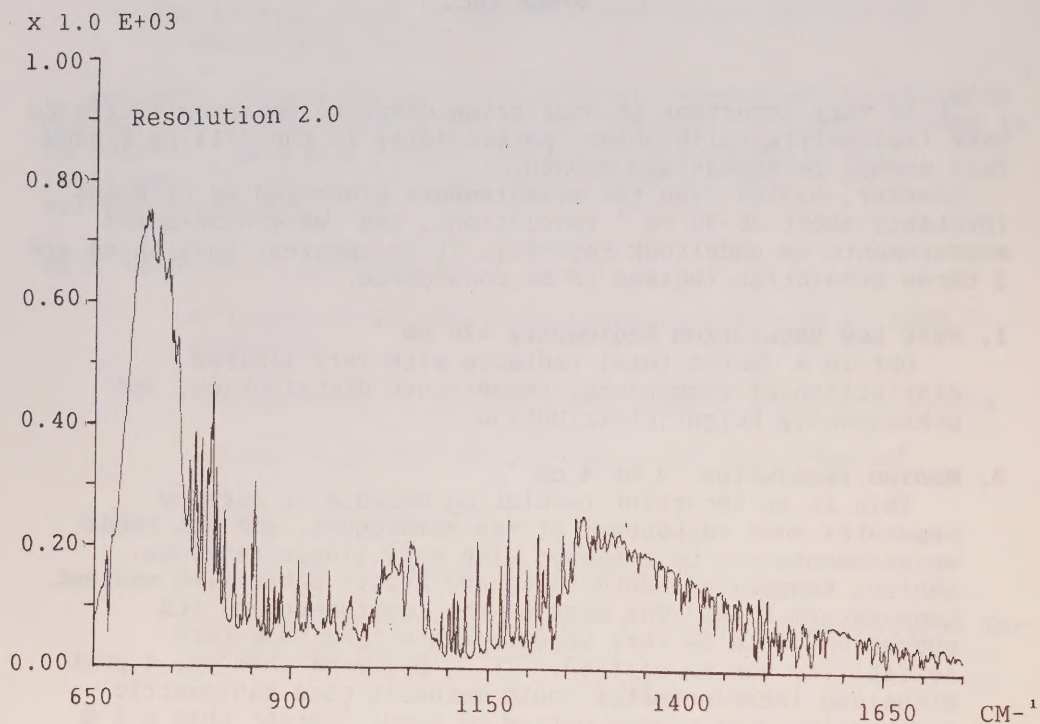
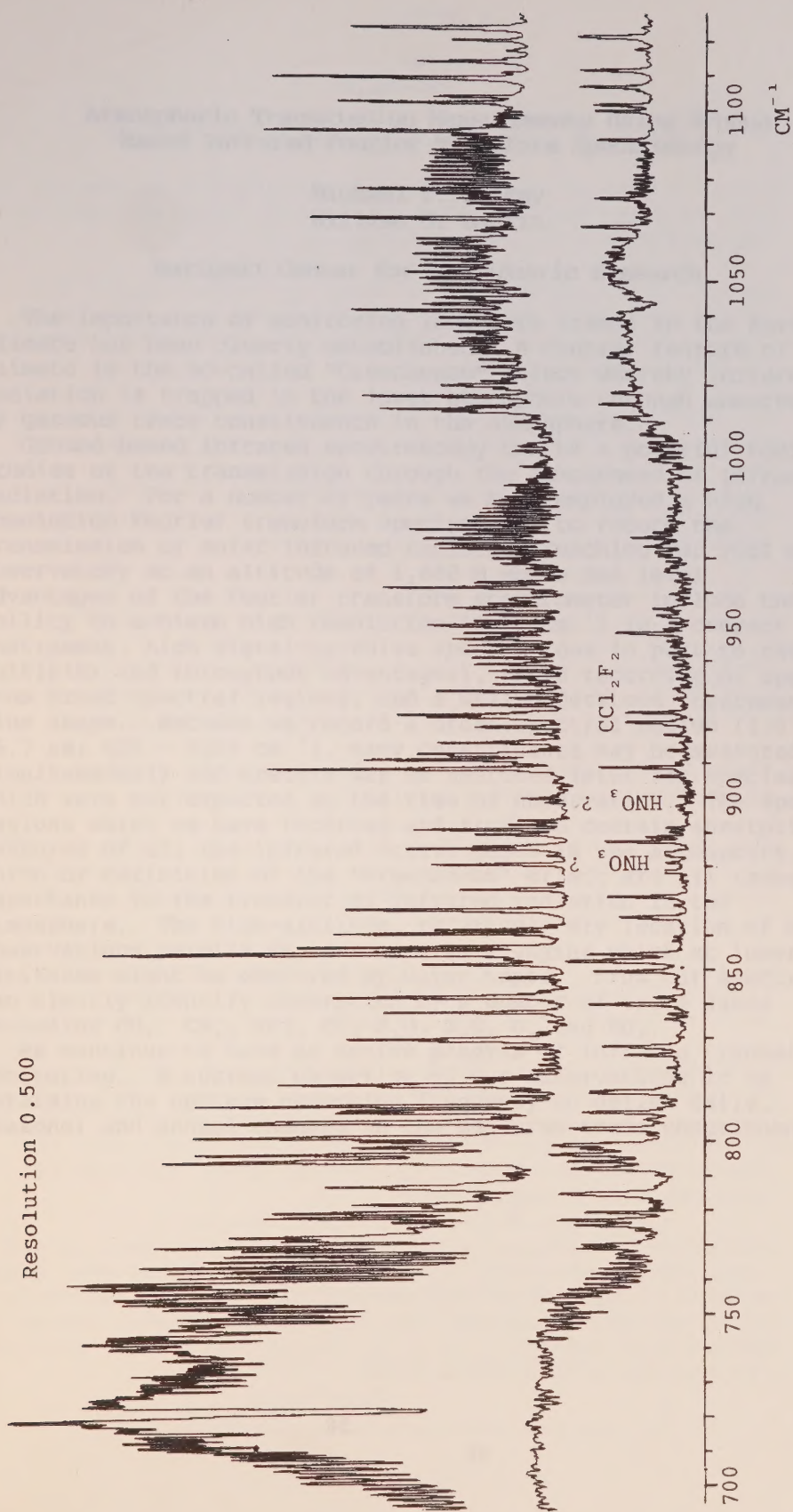
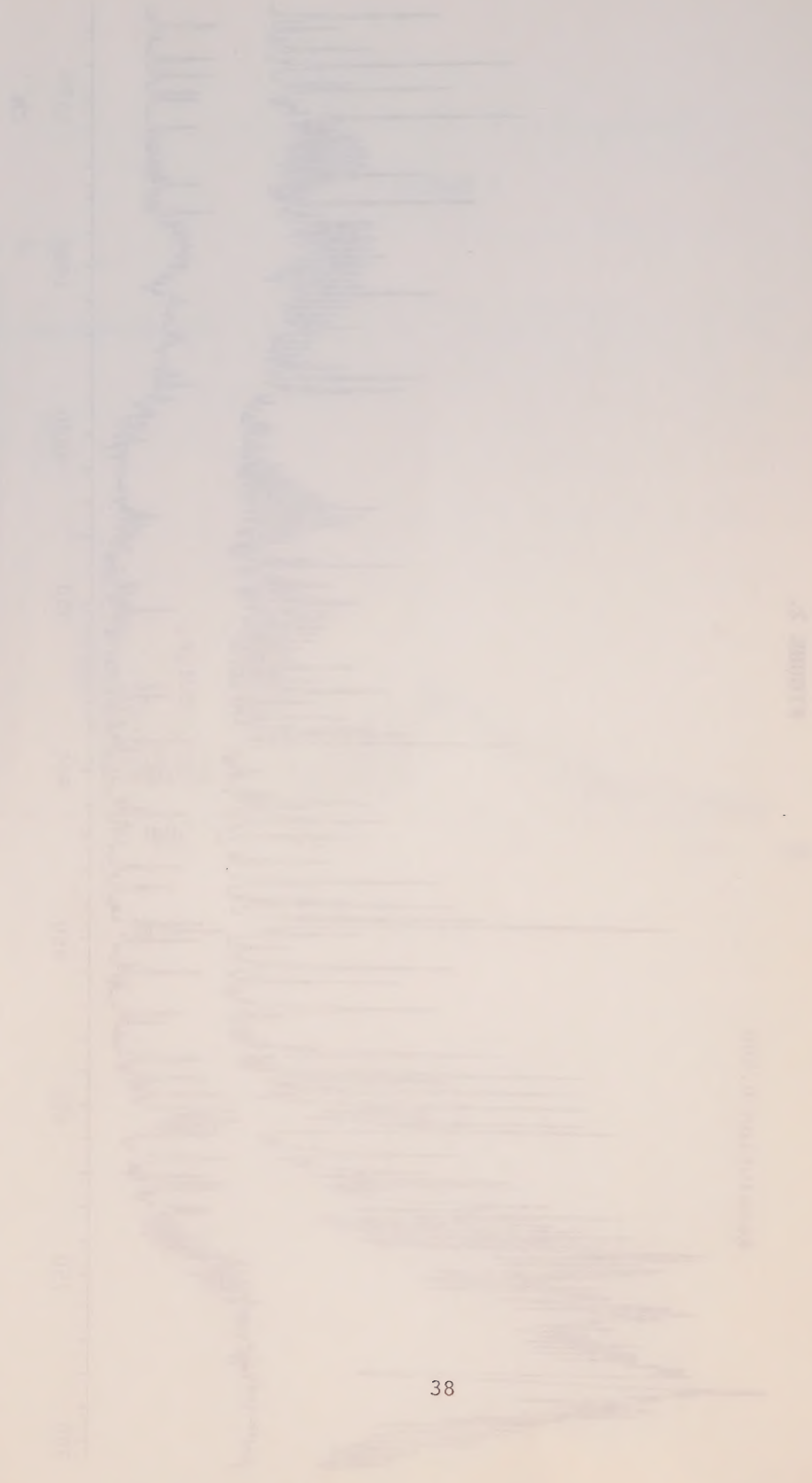


FIGURE 2.





Atmospheric Transmission Measurements Using Ground Based Infrared Fourier Transform Spectroscopy

Michael T. Coffey
William G. Mankin

National Center for Atmospheric Research

The importance of monitoring long-term trends in the Earth's climate has been clearly established. A central feature of climate is the so-called "Greenhouse" effect whereby infrared radiation is trapped in the lower atmosphere through absorption by gaseous trace constituents in the atmosphere.

Ground-based infrared spectroscopy can be a powerful tool for studies of the transmission through the atmosphere of infrared radiation. For a number of years we have employed a high resolution Fourier transform spectrometer to record the transmission of solar infrared radiation reaching our roof top observatory at an altitude of 1,880 m above sea level. Advantages of the Fourier transform spectrometer include the ability to achieve high resolution (0.06 cm^{-1}) in a compact instrument, high signal-to-noise spectra (due in part to the multiplex and throughput advantages), rapid recording of spectra from broad spectral regions, and a well understood instrument line shape. Because we record a broad spectral region ($2.0 - 16.7 \text{ }\mu\text{m}$; $600 - 5000 \text{ cm}^{-1}$), many constituents may be measured simultaneously and spectra may be searched later for species which were not expected at the time of observation. The spectral regions which we have recorded and archived contain absorption features of all the infrared active gases in the atmosphere, which by definition of the "Greenhouse" effect are all those of importance to the transfer of infrared radiation in the atmosphere. The high-altitude, relatively dry location of our observations permits us to record wavelengths which at lower altitudes might be obscured by water vapor. From our spectra we can clearly identify absorption by a number of trace gases including CO_2 , CH_4 , HCl , CO , H_2O , N_2O , O_3 and NO_2 .

We continue to have an active program of infrared transmission monitoring. A current objective of our observations is to determine the optimum observing frequency to define daily, seasonal and annual changes in the measured trace constituents.

APPENDIX

GOALS OF A "GREENHOUSE" MONITORING PROGRAM

1. Identify and prioritize the key atmospheric parameters that must be monitored in order to observe important changes in the atmospheric infrared transmission.
2. Determine the magnitudes of possible trends in the key chemical species, and determine the accuracy, precision, spatial resolution, and frequency of measurements required to detect these trends.
3. Determine the number and locations of stations required to establish a useful network.
4. Evaluate currently available measurement techniques to determine their capability to satisfy the requirements, and identify new instrumentation required.

LEGEND TO FIGURE 1.

1. Observations from the roof of the Mesa Laboratory at the same solar zenith angle. Record of spectrum from 2 to 15 μm on every clear working day for several months.
2. These denote the principal absorption bands in the atmosphere and the major atmospheric windows.
3. For the mean temperature of the atmosphere (245K) the peak of the blackbody emission is in the 10-12 μm atmospheric window making the transmission in that region very important to radiative heat balance.
4. The water vapor continuum calculation is for an average mid-latitude temperature and water amount. Being strongly related to water partial pressure and temperature it is particularly important in the tropics, for a wet tropical atmosphere transmission of a vertical path may only be 50% in the 10-12 μm region.
5. These arrows denote the locations of bands suitable for ground based constituent monitoring, other may also be measurable from the ground.
6. Radiative heating and cooling are nearly balanced at mid-latitudes. An excess solar energy is absorbed over that emitted in equatorial regions and must be transported to polar regions to account for the deficit between energy emitted and received, this, of course, drives the general circulation of the atmosphere.

FIGURE 1.

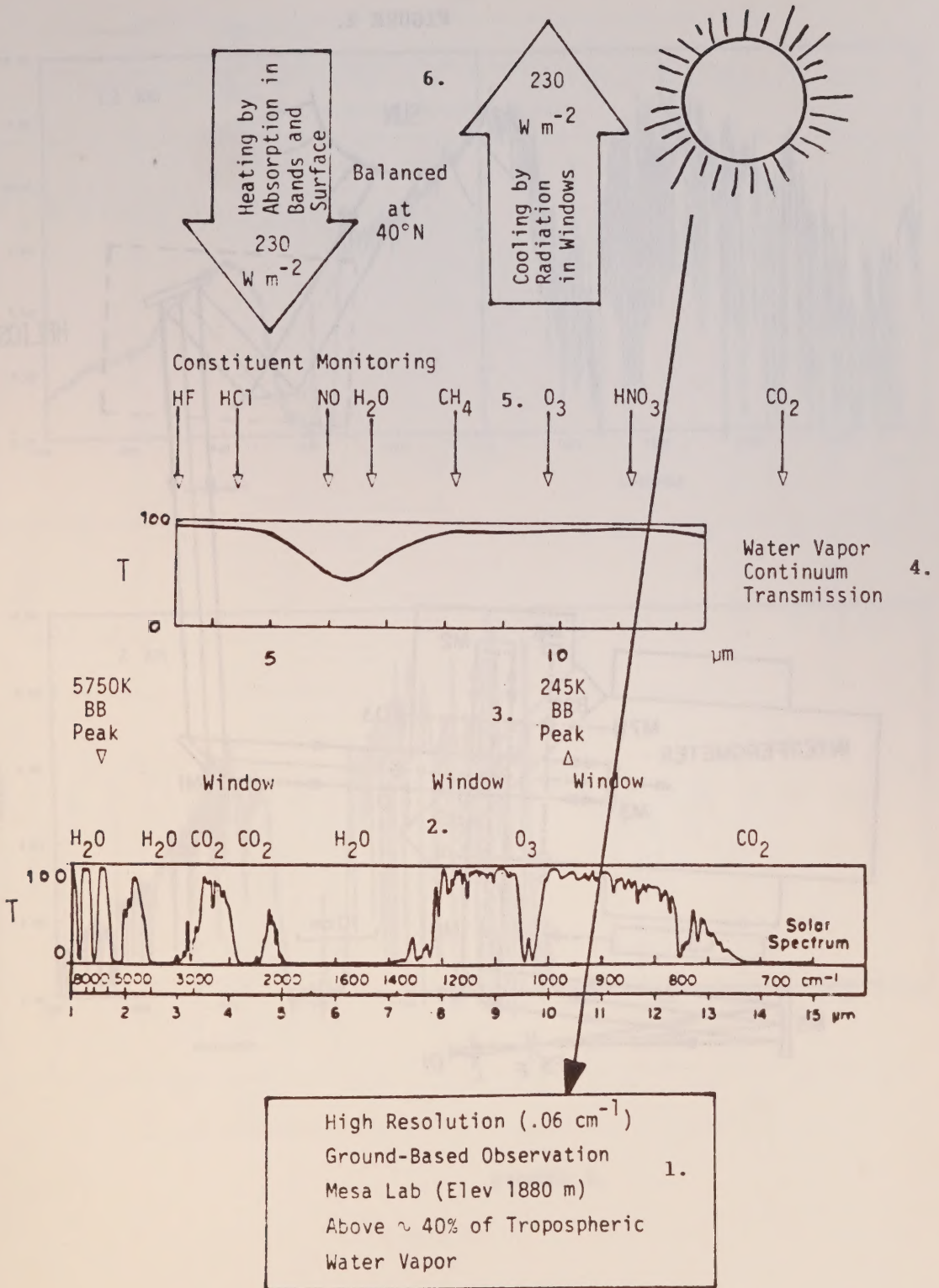
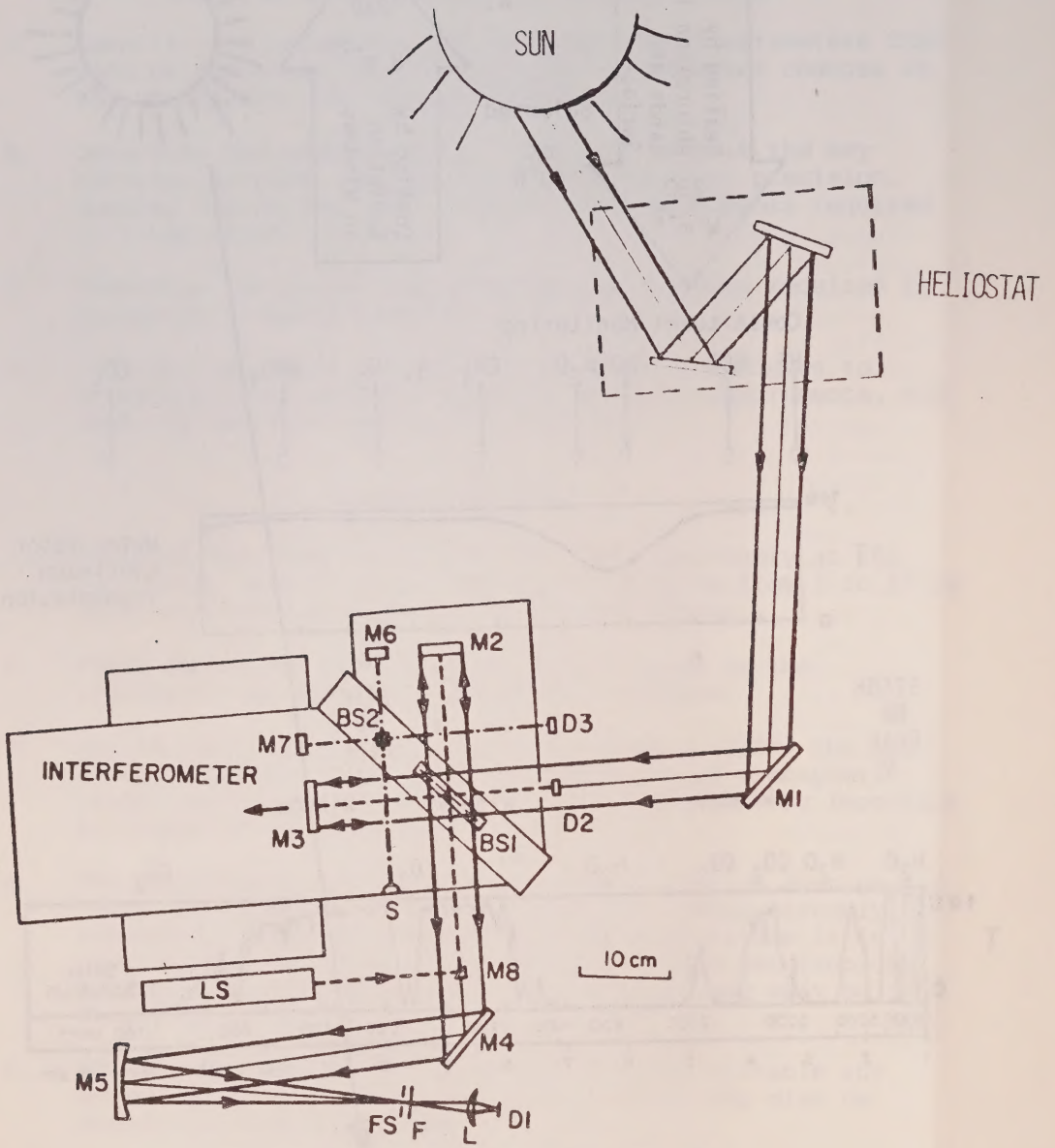


FIGURE 2.



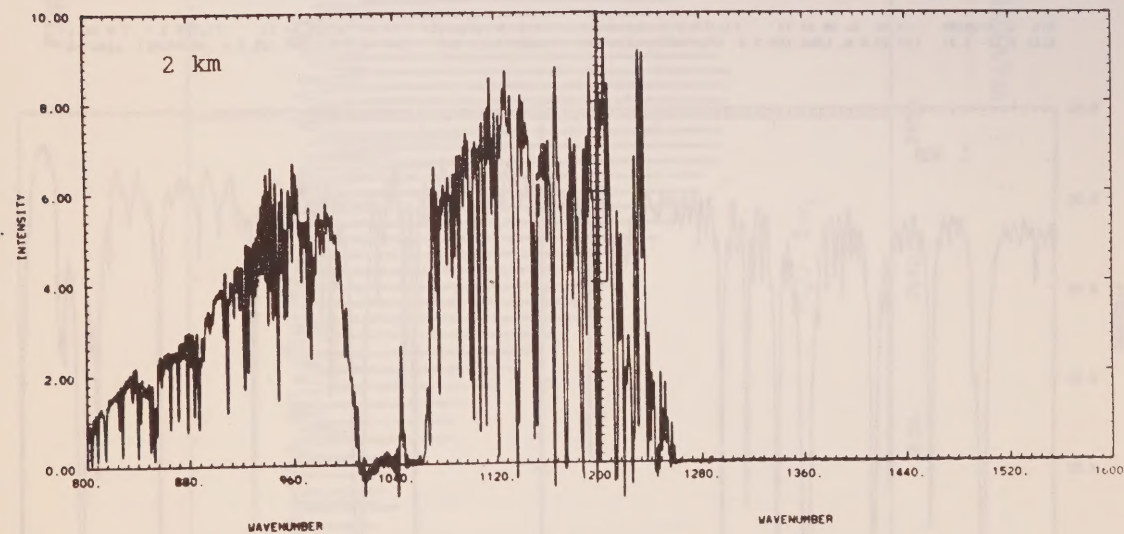
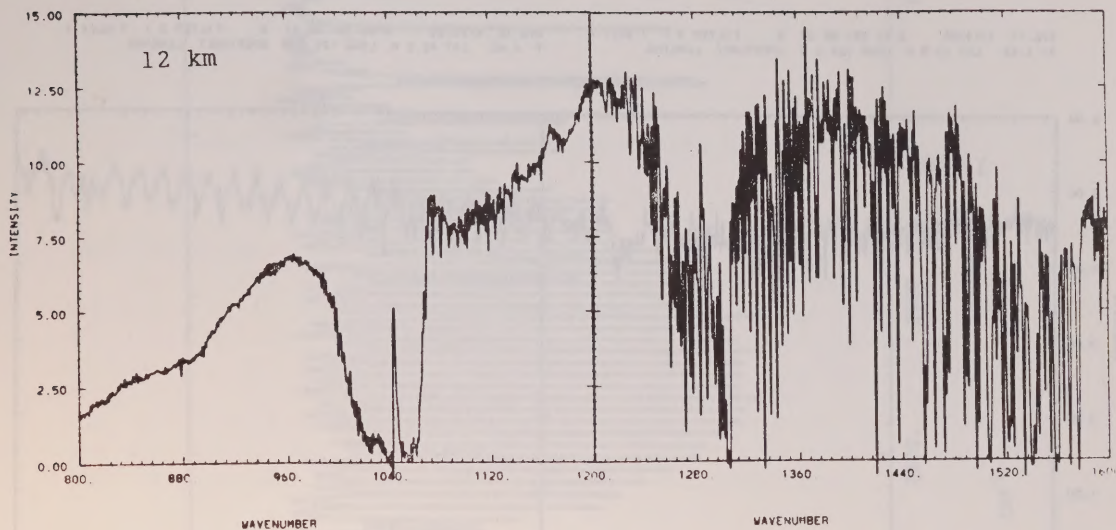


FIGURE 3.

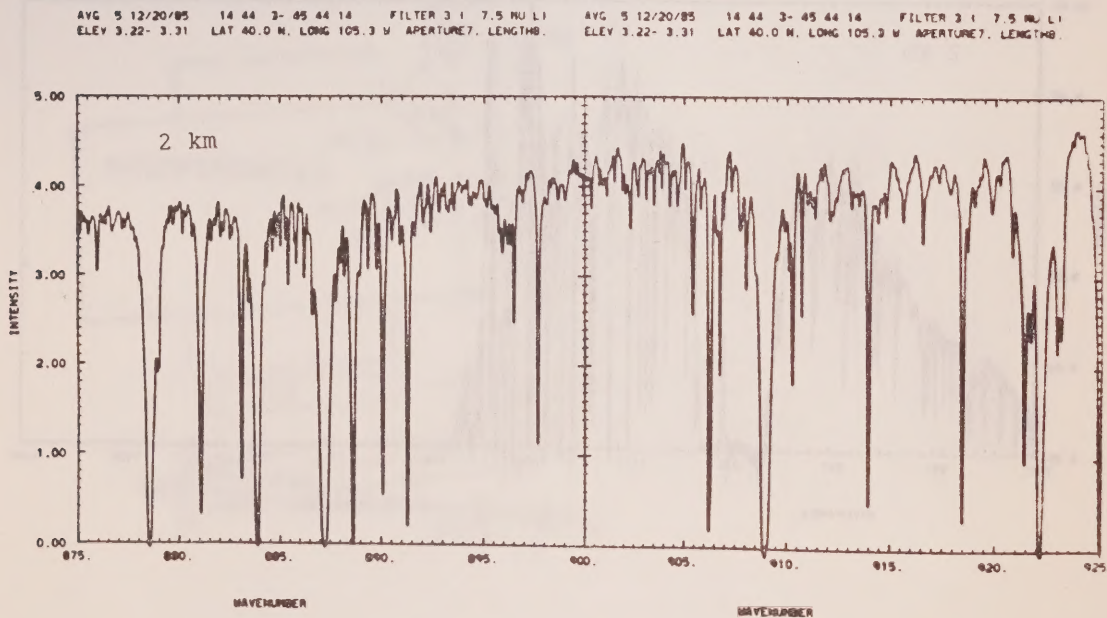
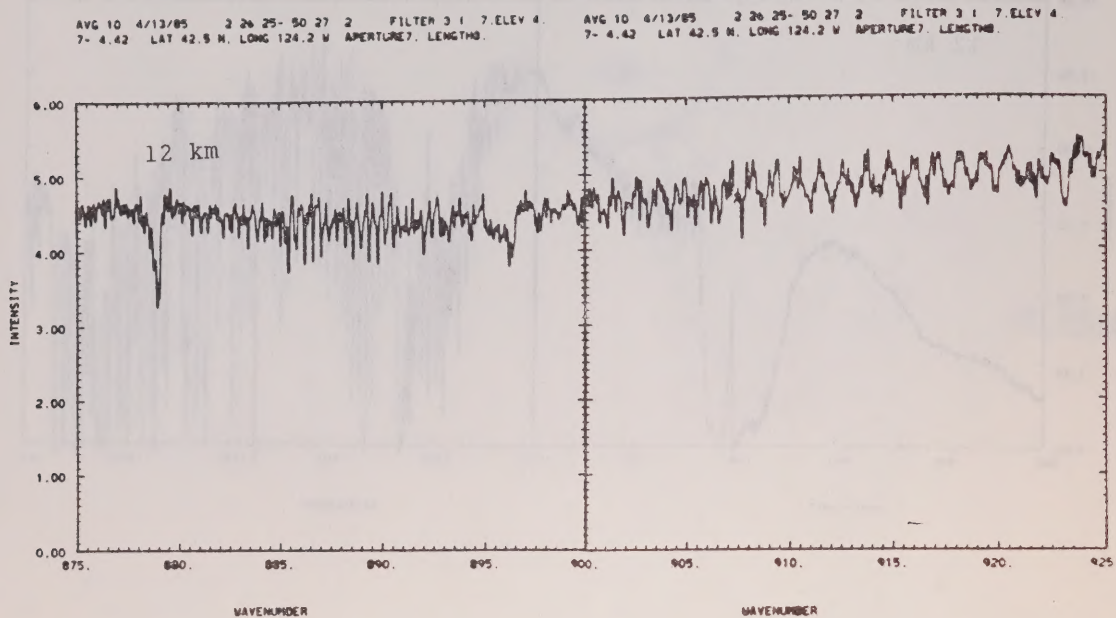
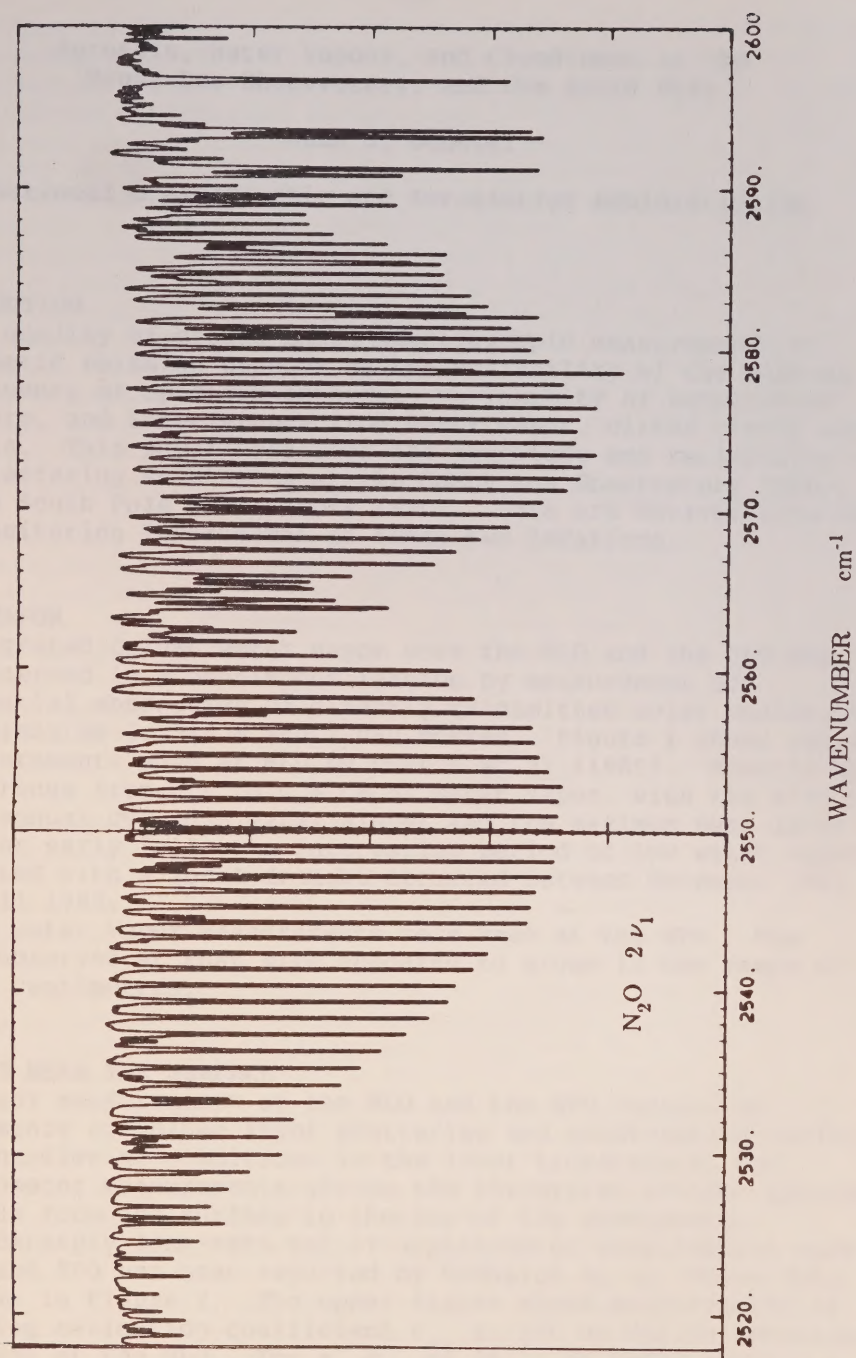


FIGURE 4.

FIGURE 5.





Aerosols, Water Vapour, and Cloudiness at the Mauna Loa Observatory, and the South Pole

John J. DeLuise

National Oceanographic and Aeronautics Administration

INTRODUCTION

The quality of ground-based spectroscopic measurements of atmospheric emission depends on the variability of the gaseous constituents of specific interest, variability of temperature structure, and interference from water vapor, cirrus clouds and aerosols. This paper describes the magnitude and variability of the interfering substances at the Mauna Loa Observatory (MLO), and the South Pole Observatory (SPO). Data are derived from the GMCC monitoring instruments at those two locations.

WATER VAPOR

Integrated column water vapor over the MLO and the SPO has been observed in a continuous fashion by measurement of differential absorption of directly transmitted solar radiation at wavelengths 1.1344 μ m and 1.060 μ m. Figure 1 shows results of measurements made at MLO by Dutton *et al.* (1985). Monthly mean values range from 0.1 to 0.4 cm of water vapor, with the minimum of the annual cycle in early winter and the maximum near later summer or early fall. An interesting period of low water vapor associated with a local drought occurred between December 1982 and April 1983.

Some water vapor measurements were made at the SPO. The values observed at that site appeared to group in the range of 0.1-0.2 centimetres.

AEROSOLS NEAR THE SURFACE

Aerosol measurements at the MLO and the SPO consist of measurements of volume light scattering and condensation nuclei representative of conditions in the lower troposphere, and sunphotometer measurements giving the integrated aerosol optical thickness from the surface to the top of the atmosphere.

A moderately long-term set of nephelometer measurements made at MLO and SPO has been reported by Bodhaine *et al.* These data are shown in Figure 2. The upper figure shows measurements of scattering extinction coefficient σ_{sp} at 550 nm during downslope conditions at the MLO. For a σ_{sp} of 10^{-6} , it would require a linear path of 100 km to achieve an optical thickness of 0.10. For contrast, in a polluted urban atmosphere, the linear path would be $\sim$ 1-10 kilometres. It is interesting to compare these values with the El Chichón cloud which was 0.75 km at 25 km over the MLO on 9 April 1986.

Condensation nuclei counts are one to two orders of magnitude lower than those found over continental areas and polluted areas.

The dashed lines are linear least squares trend analyses for the data. So far, no significant trends have been seen in these measurements at any of the four GMCC observatories.

At the SPO, the surface air is often cleaner than at the MLO. The bottom plot in Figure 2 shows data obtained at the SPO. During austral winter, occasional short bursts of higher light-scattering values, on the order of 10 times higher than normal, are recorded. Because high values of sodium are associated with these bursts, it is believed that the air is of marine origin. Nevertheless, the air is still extremely clean, even during the burst. Note that the condensation nuclei measurements at the SPO have a very regular cycle that follows the solar cycle, while at the MLO there does not appear to be a discernible cycle.

AEROSOL OPTICAL DEPTH

Aerosol optical depth is defined as the vertical column extinction coefficient for the entire depth of the atmosphere. Optical thickness is defined as a vertical column extinction for a portion of the entire depth of the atmosphere.

At Mauna Loa, the normal annual cycle of tropospheric aerosol optical thickness at 700 nm ranges from a maximum of 0.010 ± 0.006 in May, to a minimum of $0.0030 - 0.0036 \pm 0.0004$ from August to February. A minimum or background stratospheric aerosol optical thickness determined from lidar data was found to be about 0.004 ± 0.002 . These values are extremely low, exemplifying the extremely clear conditions that can prevail over the MLO. However, during extremely perturbed stratospheric conditions affected by volcanic aerosols such as from El Chichón, the aerosol optical depth observed at the MLO has been seen to increase more than 2 orders of magnitude, reaching values as high as 0.5! An event such as this is rare, having occurred only once since observations began in 1958. Nevertheless, the presence of volcanic aerosols is easily detected at the MLO. Figure 3 shows a long-term record of MLO solar transmission observations. This record clearly reveals the presence of stratospheric aerosols from Agung (3/63), De Feugo (10/74), and El Chichón (3,4/82). Other but smaller events are also seen in this record.

At the SPO, aerosol optical depths at 695 nm during austral summer were observed to be 0.008. Increases due to volcanic stratospheric aerosols were observed by pyrhelimeters to be on the order of 0.2 for Agung and 0.044 for El Chichón. These measurements represent an equivalent optical thickness over the entire range of transmitted solar radiation.

CIRRUS CLOUD FREQUENCY

A study of clear-sky and cloudy-sky transmittance at the MLO was performed by Thompson & Cox (1982). They used continuous pyrhelimetric measurements of directly transmitted solar radiation and used a model of transmittance vs. solar zenith angle to distinguish clear-sky, thin-cloud, and thick-cloud conditions. At a solar zenith angle of zero degrees, clear-sky transmittance is 0.79-0.87; thin-cloud transmittance is 0.03-0.79; and thick-cloud transmittance is 0.0-0.03. For increasingly larger zenith angles the transmittance ranges take on increasingly lower values.

Figure 4 is a frequency diagram for clouds over the MLO and is based on the three conditions described above. Table 1 summarizes the results in terms of fractional mean occurrence over the five years of observations. Of course, these results are for daylight hours. Results for full days could conceivably produce some differences.

Stebbins and Wilson (1983) examined the SPO pyrhelimetric data and produced frequency diagrams showing frequency of uninterrupted viewing segments of time for a four-year period. An intensity drop of 30 percent lasting for one minute, or 60 minutes, delimited a time period of continuously cloud-free conditions. The results are shown in Figure 5, which was taken from Stebbins and Wilson (1983). For the one-minute criterion, there were three time segments lasting longer than 90 hours. For the 60-minute criterion, there were ten time segments lasting longer than 100 hours. Both results are for a four-year period. Their work was directed at the feasibility of measuring long-period brightness oscillations at the solar limb.

REFERENCES

- Stebbins, R., and Wilson, C. (1983). The measurement of long-period oscillations at Sacramento Park Observatory and South Pole. Solar Physics, 82: 43-45.
- Bodhaine, B.A. (1983). Aerosol measurements at four background sites. J. Geophys. Res., 88: 10,753-10,768.
- Dutton, E.G., and DeLuise, J.J. (1985). Interpretation of Mauna Loa transmission relative to aerosols, using photometric precipitable water amounts. J. Atmos. Chem., 3: 53-68.
- Thompson, T.M., and Cox, S.K. (1982). Subtropical Climatology of direct beam solar radiation. J. Appl. Meteor., 21: 334-338.

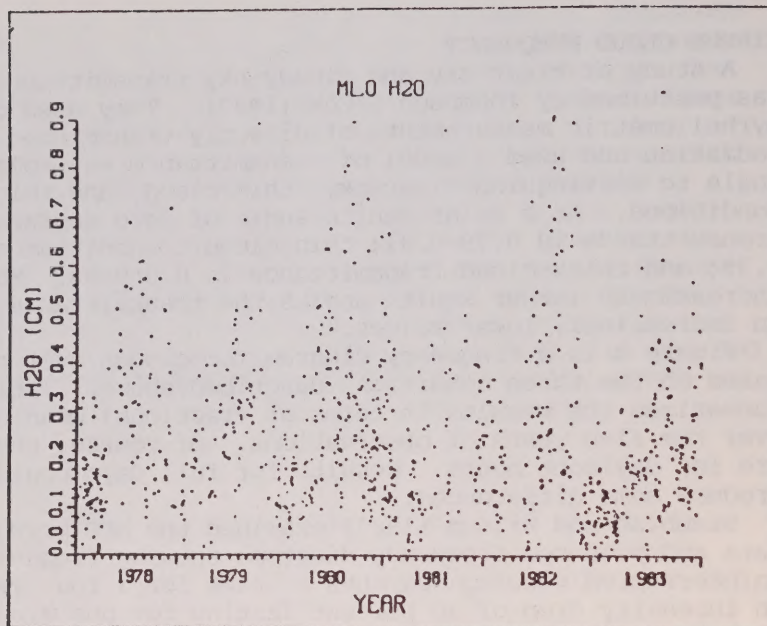


Figure 1 Precipitable water for MLO for days that an ATF was available. Values are averaged over times during which the ATF data were acquired.

MLO

TABLE 1 Fractional mean occurrence of clouds and clear skies and their variability over the five years.

Data set	Mean frequency of occurrence	Standard deviation
Clear sky	0.563	0.153
Thin cloud	0.206	0.077
Thick cloud	0.231	0.106

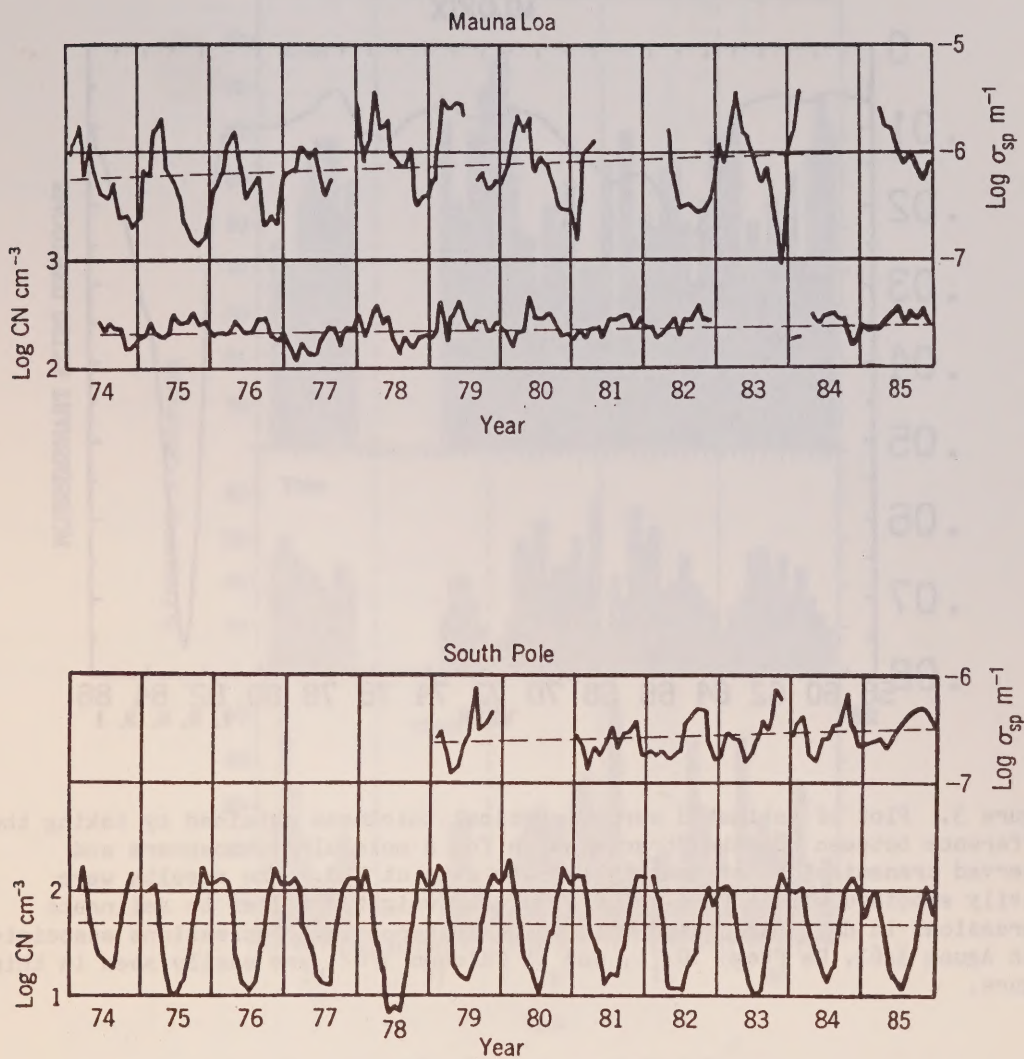


Figure 2. Plots of light-scattering extinction coefficient σ_{sp} (km⁻¹) at 500 nm and condensation nuclei CN counts measured at Mauna Loa and South Pole.

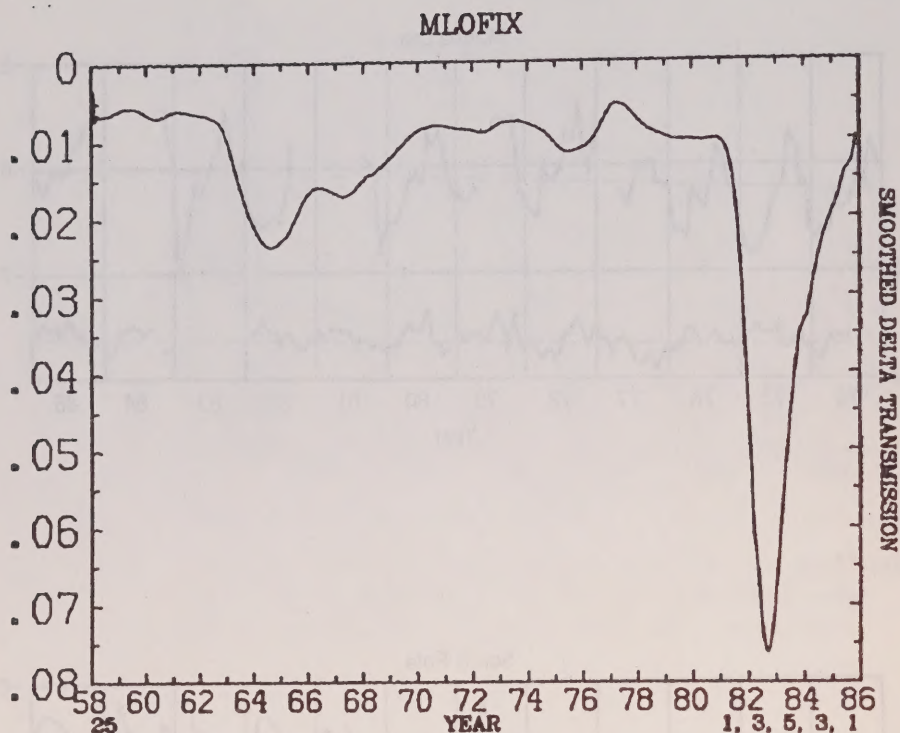


Figure 3. Plot of estimated aerosol optical thickness obtained by taking the difference between computed transmission for a molecular atmosphere and observed transmission for monthly average data at MLO. The results were heavily smoothed with a five-point 1-3-5-3-1 weighted filter to delineate depressions in data associated with volcanic aerosols. Depressions associated with Agung 3/63, De Fuego 10/74, and El Chichón 3/82, are easily seen in this figure.

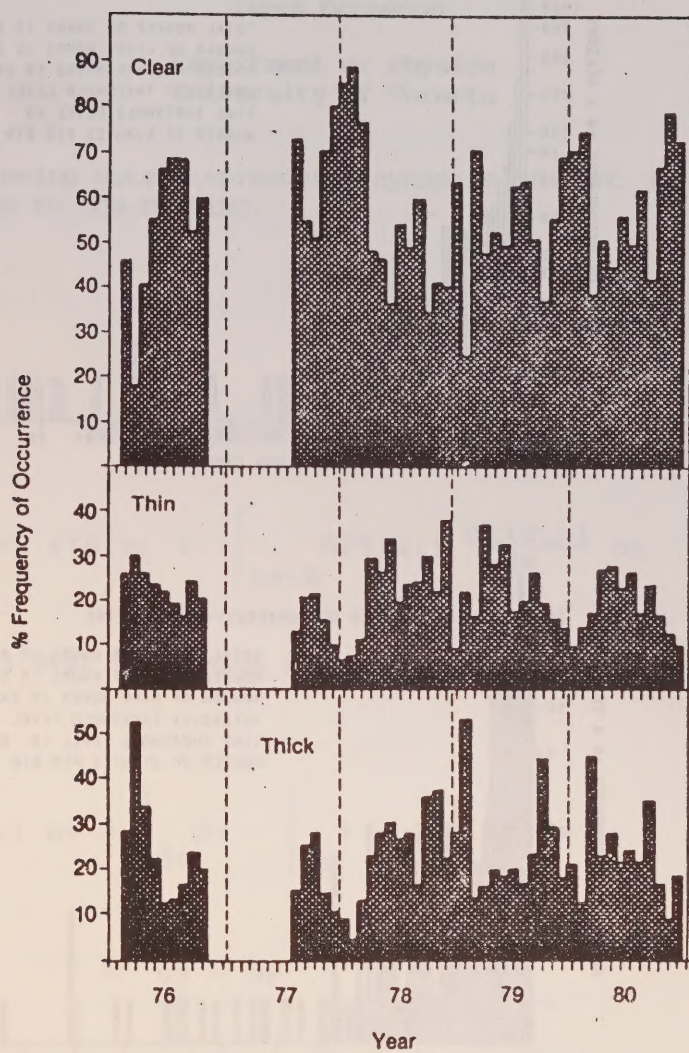


Figure 4 Time series of monthly clear and cloud frequency of occurrence.

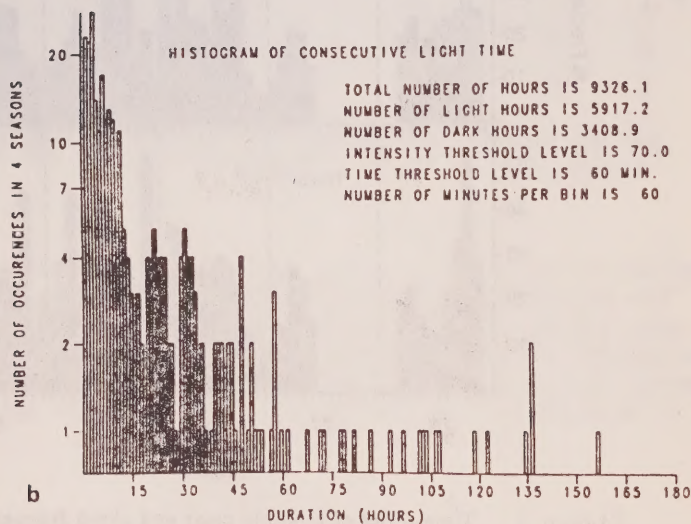
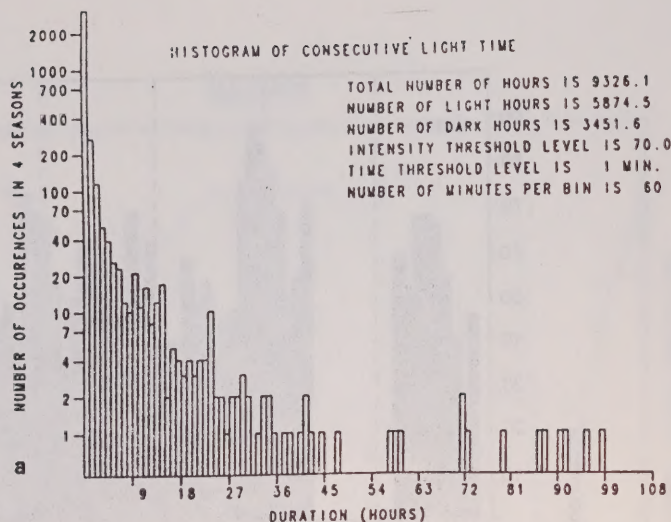


Figure 5 The frequency of occurrence of clear skies with a given duration are shown in these histograms. The threshold defining clear skies is about 70% of normal light level. (a) An intensity drop below the threshold in any one-minute sample delimits a period of clear skies in this histogram. (b) An intensity drop lasting longer than 60 min delimits clear skies in this histogram. Four Antarctic summers (November, December, and January, 1977-78 to 1980-81) are shown here.

The GENLIN Radiation Programme

James Drummond

Department of Physics
University of Toronto

The following notes represent a synopsis of Prof. Drummond's presentation to the meeting.

MONOCHROMATIC INTENSITY EQUATION

$$I(0) = I(\infty) \tau(0, \infty) + \int_{\text{path}} B(T(x)) \frac{d\tau(0, x)}{dx} dx$$

Integrate τ over v assuming δ narrow so that B and $I(\infty)$ do not change.

$$\begin{aligned} \int_{\delta v} \tau(0, x) dv &= \int_{\delta v} dv - \int_{\delta v} 1 - \tau(0, x) dv \\ &= \delta v - \delta W \end{aligned}$$

$$\overline{\tau(0, x)} = 1 - \delta W / \delta v$$

┆
Equivalent
Width

EQUIVALENT WIDTH EQUATION

$$\delta W = \int_{\delta v} 1 - \exp \left[- \sum_i \int_0^x k_i o_i(x) dx \right] dv$$

i = a sum over all lines and continua of all constituents. For a line:

$$k(v) = S f(v - v_0)$$

S is line strength, f is the shape function, v_0 is the line centre. f is one of:

Collision	(α_i)
Doppler	(α_d)
Voigt	(α_d, α_i)

For each line we need:

$$v_0 \quad S(T) \quad \alpha_i(p, T) \quad \alpha_d(T)$$

$$0.001 < p < 1.0 \quad 200 < T < 300$$

dependencies usually around $0.5 < n < 2$

STRATEGIES FOR COMPUTING W

- Analytic models (single formula)
- Extended analytic models (1 num. $\int$)
- Independent line models (n numerical $\int$)
- General line-by-line models (N $\int$)

ANALYTIC MODELS

- Ignore temperature effects
- Assume single, uniform, analytic line shape
- Assume analytic line strength distribution
- Ignore line overlap (except in simplest terms)

ANALYTIC MALKMUS MODEL

- Assumes line strength distribution as:

$$\frac{N_o}{S} \exp \left(- \frac{S}{\delta} \right)$$

- Assumes collision lineshape:

$$\frac{\alpha_1 / \pi}{(v - v_o)^2 + \alpha_1^2}$$

- Equivalent width given by:

$$2\pi\alpha_1 N_o \left[\left[1 + \frac{\sigma u}{\pi\alpha_1} \right]^{1/2} - 1 \right]$$

- Band parameters are δ/α_1 and $N_o\alpha_1$.
- Band parameters usually found by matching at strong and weak limits.

SHORTCOMINGS OF ANALYTIC MALKMUS MODEL

- Lines are assumed independent (no overlap). Can be roughly accounted for by:

$$\bar{\tau} = 1 - \delta W / \delta v \approx \exp (-\delta W / \delta v)$$

- Does not account for structure in path.
- Works best for large numbers of lines but needs spectral intervals to be narrow.

RESOLVING PROBLEMS

- Use Curtis-Godson approximation to reduce structural path to homogeneous:

$$\bar{u} = \int \rho \, dx , \quad \bar{p} = \int p \, \rho \, dx / \bar{u}$$

- Use a different formula for line overlap. e.g. a different δv in the exponential.
- Use extended model to account for path explicitly.

EXTENDED MALKMUS MODEL

- Assumed line strength distribution as:

$$\frac{N_o}{S} \exp \left(- \frac{S}{\delta} \right)$$

- Equivalent width formula:

$$\delta W = N_o \int_{-\infty}^{\infty} \ln \left[1 + \sigma \int f \, du \right] dv$$

- Allows the use of a single lineshape which need not be collision and can vary along the path.
- Band parameters are σ , α_1 and N_o .
- Band parameters usually found by matching at strong and weak limits plus some idea of the average value of α_1 or by a minimisation of the errors between actual and model results.

INDEPENDENT LINE MODEL - 1

- Assumes independent lines.
- Shape function common to lines of similar strength.
- Separates lines of similar shape into bins (a histogram)

$$\delta W = \sum_{\text{lines}} \delta W_i = \sum_{\text{bins}} n_j \delta W_j$$

- Number of bins: e.g., log spacing, 4/decade.
- Can account for structural paths, complex instruments, esp. correlation types such as SCR, PMR.

INDEPENDENT LINE MODEL - 2

- Spectral width can be increased if spectral variation of radiation is known, e.g., is blackbody in nature, by weighting n_j :

$$n_j = \sum_i \frac{B(v_{oi}, T_i)}{B(v_s, T_i)}$$

v_s is standard wavenumber e.g., band centre.

- 1st order temperature corrections to linestrength can be applied.

INDEPENDENT LINE MODEL - SHORTCOMINGS

- Line shape must be the same for all lines in one bin.
- Does not account for overlap except through exponential formula. Does well for CO, less well for O₃.
- Consumes more computer time and needs more setting up.

GENERAL LINE-BY-LINE MODEL

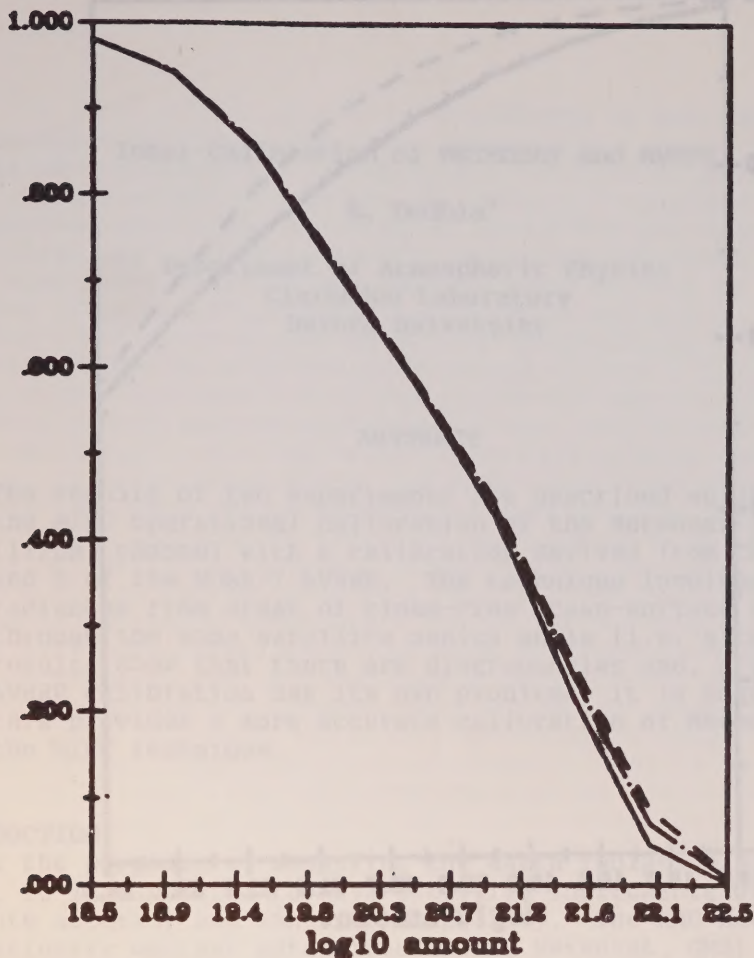
- Only approximations are numerical and by choice. Accuracy limited ultimately by input data.
- Accounts explicitly for individual line shape and overlap, mixed gases and continua.
- Accounts explicitly for structural path including full T dependence.
- Ultimately capable of accounting for any instrument function.
- Consumes a lot of computer time - but programs are better and time is cheaper.

GENLIN LBL MODEL - 1

- Computes emission, transmission or both (U)
- Divides path up into 1-component, homogeneous cells (U)
- Calculates multiple paths simultaneously.
- Spectrum is divided into intervals of $\delta\nu_0(U)$ containing many lines. Lines up to at least $\pm \delta\nu_0$ are accounted for explicitly.
- Accounts for SCR, PMR, WB instruments and Doppler shifts.

GENLIN LBL MODEL - 2

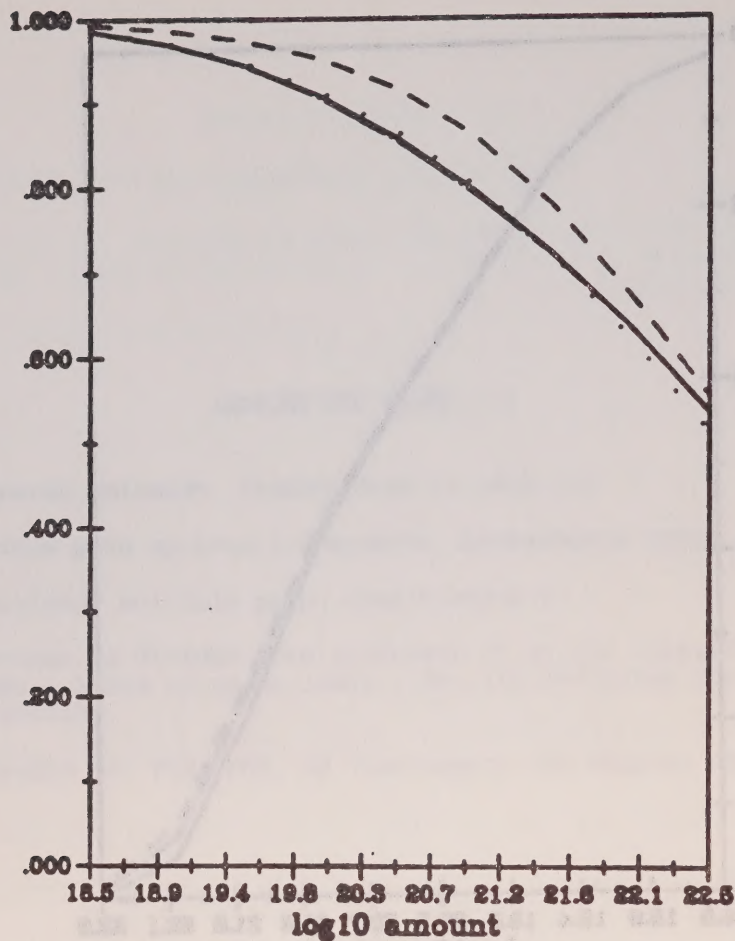
- Uses a fine grid in spectral space $\delta\nu_s(U)$.
- Accounts for lines (Voigt profile at present) and continua.
- Uses practically any spectral data format (U).
- Linearly interpolated contribution from "far out" lines.



Comparison at 1.0 atm by spectral sections of 5 cm^{-1}
 GENLIN (solid)
 Simple Malkmus (dashed)
 Extended Malkmus (dotted)
 Independent Line (dash-dot)

Comparison at 1.0 atm

Mass	GENLIN	S-M	E-M	IND
18.5	.98005	.98080	.98087	.98087
19.0	.94174	.94393	.94410	.94388
19.5	.85208	.85765	.85804	.85645
20.0	.71355	.72224	.72267	.71920
20.5	.58123	.58755	.58793	.58481
21.0	.42948	.44608	.44664	.44093
21.5	.21997	.25944	.26000	.24534
22.0	.04629	.08747	.08785	.07104
22.5	.00170	.01224	.01238	.00740



Comparison at 0.001 atm by spectral sections of 5 cm^{-1}
 GENLIN (solid)
 Simple Malkmus (dashed)
 Extended Malkmus (dotted)
 Independent Line (dash-dot)

Comparison at 0.001 atm

Mass	GENLIN	S-M	E-M	IND
18.5	.98566	.99299	.98690	.98561
19.0	.97007	.98605	.97214	.96941
19.5	.94536	.97365	.94843	.94395
20.0	.90858	.95220	.91377	.90619
20.5	.85824	.91652	.86595	.85497
21.0	.79607	.86009	.80203	.79237
21.5	.72261	.77811	.71977	.72031
22.0	.63459	.67231	.62042	.63487
22.5	.53468	.55446	.51288	.53650

Inter-Calibration of METEOSAT and AVHRR

A. Dudhia¹

Department of Atmospheric Physics
Clarendon Laboratory
Oxford University

ABSTRACT

The results of two experiments are described which compare the MIEC operational calibration of the Meteosat-2 IR1 (11 μm) channel with a calibration derived from Channels 4 and 5 of the NOAA-7 AVHRR. The technique involves comparing radiances from areas of cloud-free ocean-surface viewed through the same satellite zenith angle (i.e. airmass). The results show that there are discrepancies and, although the AVHRR calibration has its own problems, it is suggested that this provides a more accurate calibration of Meteosat than the MIEC technique.

INTRODUCTION

For the purposes of measuring the earth radiation budget (ERB), it is essential to have satellite instruments of high absolute accuracy and long-term stability. The WMO network of geostationary weather satellites (GOES, Meteosat, GMS) are ideally situated to monitor the radiation budget but tend to suffer from poor calibration and consequently numerous experiments have been carried out to intercalibrate these satellites using the, usually, better calibrated NOAA series of polar orbiters. Even if unable to provide an absolute calibration, a single polar orbiter passes through the FOV of all the geostationary satellites, as well as covering the polar regions, and can therefore be used to provide a consistent calibration for all the satellites.

The technique of comparing satellite calibrations by simultaneously viewing the same point on the earth's surface is well established. Apart from the ERB experiments which compare both shortwave (visible) and longwave (11 μm) radiances (e.g. Saunders *et al.*, 1983; Brooks *et al.*, 1984), attempts to use two-satellite methods for sea-surface temperature (SST) measurement generally couple the 11 μm channel measurements of a NOAA satellite and either Meteosat (Saunders *et al.*, 1982; Beriot *et al.*, 1982; Holyer, 1984). This paper describes a comparison of the calibrations of the 11 μm channels of Meteosat-2 and the NOAA-7 AVHRR.

1. Paper communicated by Dr H. Roscoe

MIEC CALIBRATION OF METEOSAT-2

Meteosat-2 is a geostationary weather satellite, operated by ESA, situated above the intersection of the equator and the Greenwich meridian. The IRI (11 μm) channel has a ground resolution at the sub-satellite point of 5km and an instrumental noise equivalent temperature of 0.3 K at 290 K. The calibration procedure is fairly complex, described in ESA (1976), but, in the following, a simplified form is presented. Potentially every 30 minutes, but usually only once or twice a day, a warm (~290 K) black-body is inserted into the optical path at a point between the main optics and the detector/filter. The resulting signal is compared with that from a 'cold' target provided by reflecting the detector cold-patch (~90 K, essentially zero radiance at 11 μm) back on to itself. The difference can be used to monitor the component of gain due to the detector but does not take into account the main optics, and therefore an external calibration target is required. The Meteosat Information Extraction Centre (MIEC), at Darmstadt, collects ship measurements of SST and, using a suitable correction for atmospheric effects, calculates the radiance reaching the satellite from these cloud-free areas of ocean. This is used to produce an absolute calibration which is updated every few months (Fea, 1982). The calibration is expressed as:

$$R'(T) = FB(C(T) - S) \quad [1]$$

where:

F is a numerical factor known as the Fine Adjustment of Gain (FAG) derived from the internal calibration

B is the MIEC Slope derived from SST measurements

C(T) is the count registered by a target of brightness temperature T

S is the count from a space view, usually taken as '5'

The MIEC radiance R' has slightly unusual units ($\text{W/m}^2 \text{ sr cm}^{-1}$) but can be converted to conventional spectrally-weighted radiance R ($\text{mW/m}^2 \text{ sr.cm}^{-1}$) by dividing by an equivalent width of 56.16 cm^{-1} .

Apart from the practical difficulties of accurately converting ship measurements of SST to radiance reaching the satellite, a further, unexpected, problem has arisen in that the FAG exhibits spurious variations which are correlated with the internal black-body target temperature. This is thought to be due to the filter temperature varying with the overall satellite temperature. For most of the year the satellite is in constant sunlight and thus the temperature variation is on an annual cycle due to changing solar aspect. The result is that the MIEC slope has to be

updated rather more frequently during the year than originally anticipated to compensate for this, but the variation is slow enough for a reasonably absolute calibration to be maintained. However, for a period of a few weeks near the equinoxes, the satellite is eclipsed by the earth for a few hours every day and is subject to a strong diurnal heating cycle as well as a temporary drop in average temperature. In consequence, the value of FAG is subject to a rapid variation independent of the behaviour of the instrumental gain and it is not possible to update the MIEC slope often enough to remove this variation. Any calibration using values of FAG derived during this period is therefore suspect. It may, in fact, be more accurate to assume that the gain remains constant during the equinoxes and only uses values of FAG and corresponding MIEC slope obtained outside this period.

CALIBRATION OF NOAA-7 AVHRR/2

All the TIROS-N/NOAA series of polar orbiters, operated by the National Oceanographic and Atmospheric Administration, contain AVHRR (Advanced Very High Resolution Radiometer) instruments, the versions flown on NOAA-7 and NOAA-9 differing in that, in addition to Ch4, they have a second channel (Ch5) in the 11 μm atmospheric window. The ground resolution for all 5 channels is 1 km at the sub-satellite point and the noise equivalent temperature is ~ 0.03 K at 290 K (NOAA-7 AVHRR, Ch4 and Ch5). AVHRR uses a conventional two-point linear calibration viewing space and an on-board black-body calibration target situated outside the optical chain. Because both targets are viewed through the same optical path as the earth, unlike Meteosat, the calibration can be expressed simply as:

$$R(T) = G(C(T) - S) \quad [2]$$

where:

$$G = (R(T_b) / (C(T_b) - S))$$

and T_b is the temperature of the on-board target (~ 290 K).

These two targets are viewed during every rotation of the scan mirror (360 rpm). The on-board target has to be of a size sufficient to fill the entire FOV (> 20 cm across) and this has led to problems ensuring temperature uniformity across the whole target. The actual target temperature is monitored by 4 Pt resistance thermometers (PRTs) whose output is included in the telemetry data. The recommended calibration procedure, described in Lauritson *et al.* (1979), requires taking a simple average of all four temperatures registered by the PRTs. For NOAA-7 these show a discrepancy of ~ 1 K (see, for example, Brown *et al.*, 1985) suggesting the presence of a large temperature variation across the target. This being the case, it is unlikely that a simple average of 4 point temperatures will reproduce the mean target

temperature, as seen by the radiometer, to better than, say, 0.1 K, and is quite possibly worse. The quasi-constant nature of the PRT temperature distribution implies that the calibration will possess a temperature offset. The NOAA-6 AVHRR exhibits a similar problem, although on the NOAA-9 AVHRR all four PRT temperature lie within 0.1 K of each other.

THEORY OF INTERCALIBRATION

In the following, the brightness temperature T of a spectrally weighted radiance R is defined by:

$$R(T) = \int_0^{\infty} \theta(v) B(v, T) dv \quad [4]$$

where:

B is the Planck function

θ is the normalised spectral response ($\int_0^{\infty} \theta(v) dv = 1$)

v is the wavenumber

If a target has a black-body radiance distribution, all instruments will record the same brightness temperature; it is therefore not necessary to use instruments of similar spectral responses. Conversely, if two instruments have identical spectral responses, then any target will yield the same brightness temperature irrespective of its radiance distribution. Because neither condition can be met in full, it is necessary to compromise by using sea radiances to simulate a black-body and AVHRR Chs 4 and 5 to simulate the Meteosat IR1 response. Although the sea radiance at 11 μm just above the surface is a good approximation to a Planck distribution, the radiance at the top of the atmosphere, as seen by the satellites, is less ideal. From Fig. 1, the Meteosat IR1 response can be seen to cover the combined responses of Ch4 and Ch5. It appears reasonable, therefore, in the absence of any large spike in atmospheric absorption in the region between Ch4 and Ch5, that the brightness temperatures recorded will be related by:

$$T_1 = 1/2 (T_4 + T_5) \quad [5]$$

where:

T_1 is the Meteosat IR1 brightness temperature

T_4 , T_5 are the AVHRR Ch4, Ch5 brightness temperatures respectively.

A more detailed study, using the results of a transmission model at the Rutherford Appleton Laboratory, suggests giving more weight to Ch4 for N. Atlantic atmospheric profiles and more weight to Ch5 for tropical atmospheres, but the variations were only a few percent from equal weighting at most. Since the Split-Window difference ($T_4 - T_5$) is only a few degrees K, the errors arising from using eqn [5] are not a significant part of the overall uncertainty.

In an inter-calibration exercise, the targets are views of the earth's surface or atmosphere. It is possible to work with the raw targets covering many types of land/sea/cloud surface, this gives a wider range of radiances and therefore a better test of the linearity of the calibration, and also avoids biases that may be caused by cloud-clearing. The advantages of using only cloud-free sea pixels, as used here, are that the sea is spatially and spectrally uniform in radiance, i.e. the colocation of images does not have to be exact, and the emissivity is known to be reasonably constant over the 11 μm region, although this still leaves the problem of differential atmospheric absorption.

EXPERIMENTAL DETAILS

Two experiments were carried out. The first, based on daytime data from the NE Atlantic (June 1982), used AVHRR HRPT data, supplied by Dundee University, and the Meteosat BIV format data received at Oxford. The second, based on nighttime data from the tropical Atlantic (April 1984), used AVHRR GAC data, supplied by NESDIS, and Meteosat AI format data, also received at Oxford. For both periods, 4 Meteosat images from within a couple of hours of the NOAA-7 pass were combined to improve the S/N ratio. In the NE Atlantic data, the Meteosat airmass varied from approximately 1.2-2.0 atmospheres, and for the tropical data, 1-1.1 atmospheres. The images were cleared of clouds by a spatial coherence test (Coakley & Bretherton, 1982), and, in the case of the daytime data, a preliminary visible channel (albedo) threshold test. The remaining pixels were then grouped into 1 degree lat./long. squares and an average count for each channel derived. The AVHRR channels were calibrated and converted to brightness temperatures via the procedure described in section 3. Only the squares which possessed an airmass difference of <0.05 atmospheres for the two satellite view angles, and for which there was a high confidence in the cloud-clearing, were used. This gave several tens of targets per day.

Treating each day separately, the Meteosat brightness temperatures for each AVHRR Ch4-Ch5 pair were derived from eqn [5] and converted back to radiances. The Meteosat gain was then derived from the slope of the best straightline fit to these radiance-count data. The intercept (zero radiance) was forced to be 5 cts as there was not a sufficient range of SST temperatures to allow a realistic fit for both slope and intercept.

RESULTS

A typical plot, from 30 June 1982, is shown in Fig. 2, together with the fitted calibration slope. The vertical bars represent the T_4 - T_5 difference. The daily values of calibration slope derived from AVHRR data, are shown in table 1. It is reasonable to assume that the Meteosat calibration remains stable over these short periods, in which case the random errors in the AVHRR calibration can be gauged from the day-to-day variability of the slope. Overall, the AVHRR estimates of Meteosat Gain are $0.6938 \text{ (mW/m}^2\text{sr.cm}^{-1}\text{ct)}$ for 27-30 June, 1982, and 0.7082 for 1-5 April, 1984. The error in these quantities is estimated to be of the order of 0.0020.

COMPARISON WITH MIEC GAIN

Table 1 shows the MIEC values covering the same periods, converted to conventional units for comparison with the values derived from AVHRR radiances. For convenience, the calibrations are also expressed in terms of the brightness temperature predicted for 150 counts ($T(C=150)$).

The results for June 1982 show that MIEC predicts temperatures $\sim 2 \text{ K}$ lower than those derived from AVHRR. Starting 2 months earlier, MIEC had stopped updating their absolute calibration on a regular basis, although it was later resumed. The reason for this was that they considered that the effects of a volcanic eruption (El Chichón) in March 1982 were producing more atmospheric absorption than allowed for in their model and therefore that their radiances were biased too warm (Fea, 1982). The effect of suspending updating the MIEC slope was that the FAG, and therefore the overall gain, continued to fall in line with the on-board BBT (section 2) through June until their values were rather lower than normal. On the evidence of the AVHRR calibration, it seems that the effects of warm bias may have been negligible. While El Chichón undoubtedly influenced atmospheric absorption, its effects were confined to south of 30°N , whereas the MIEC ship SSTs come largely from the Mediterranean ($>30^\circ \text{N}$), and therefore the MIEC calibration would not have been influenced.

The tropical data show a much better agreement, this time with the MIEC radiances being slightly warmer. Although the 0600 GMT calibrations are closer in time to the night-time tropical data used for the comparisons, these are likely to be biased cold, due to eclipsing, for reasons outlined in section 2. The previous

update of the MIEC slope occurred about a month prior to the comparison, but since the on-board black-body temperature then was about the same as during the 1800 GMT calibration, implying that the FAG error was also the same, the value of slope may be reasonably accurate, assuming that variations in the true gain are small over the intervening period.

DISCUSSION

The MIEC calibration does not appear to take into account the skin-effect. Because satellite SST is naturally biased slightly cold ship SST due to this effect (for example, Robinson, et al, 1984), this suggests that the MIEC calibration produces temperatures a few tenths K too high to get the satellite SSTs to agree with the ship SSTs. This may account for the negative values in the Difference column of Table 1.

An opposite effect on the AVHRR-MIEC difference may be due to the relatively poor spatial and radiometric resolution (due to noise) of the Meteosat detector. This makes the cloud-detection less effective so that, in the comparison of AVHRR and Meteosat radiances of 1 degree squares, the Meteosat radiance should be slightly lower than has been assumed. The result is that the AVHRR calibration of Meteosat produces temperatures that are also too high, although this is not expected to amount to more than a few 100ths K, i.e. much smaller than the skin effect influence on the MIEC calibration.

CONCLUSIONS

Neither comparison was made at an optimum time from the viewpoint of assessing the general quality of the MIEC slope: in June 1982 the MIEC calibration was out of date and in April 1984 Meteosat was in eclipse mode, during which the on-board calibration behaves anomalously. Nevertheless, the agreement during the April 1984 period is surprisingly good.

The fundamental discrepancy between the MIEC calibration and the AVHRR inter-calibration of Meteosat appears to be of the order of a few tenths K, which may be due to errors in the MIEC calibration through skin effect or atmospheric corrections, or due to uncertainties in the absolute calibration of the NOAA-7 AVHRR arising from the PRT discrepancy.

Overall, the inter-calibration of Meteosat with AVHRR is feasible and, probably, less prone to systematic errors than the MIEC calibration procedure.

REFERENCES

- Beriot, N., Scott, N.A., Chedin, A. & Sitbon, P. (1982). Calibration of geostationary-satellite IR radiometers using the TIROS-N vertical sounder: application to Meteosat-1. J.App.Met., 21: 84.
- Brooks, D.R., England, C.F., Hunt, G.E. & Minnis, P. (1984). An intercalibration of Meteosat-1 and GOES-2 visible and IR measurements. J.Atmos.Tech., 1: 283.
- Brown, O.B., Brown, J.W. & Evans, R.H. (1985). Calibration of Advanced Very High Resolution Radiometer Infrared observations. J.Geo.Res., 90(11): 667.
- Coakley, J.A. & Bretherton, F.P. (1982). Cloud-cover from high resolution scanner data: detecting and allowing for partially filled fields of view. J.Geo.Res., 87: 4917.
- ESA (1976). On the problem of IR calibration of the radiometer. MET/TN/074-76/MLR-pk.
- Fea, M. (1982). Meteosat-2 calibration report - Issue 1. Meteosat Data Management Dept., Darmstadt, W. Germany.
- Holyer, R.J. (1984). A two-satellite method for measurement of SST. Int.J.Rem.Sens., 5: 115.
- Lauritson, L., Nelson, G.J. & Porto, F.W. (1979). Data Extraction and Calibration of TIROS-N/NOAA Radiometers. NOAA Tech. Memo NESS 107, Washington DC.
- Robinson, I.S., Wells, N.C. & Charnock, H. (1984). The sea surface thermal boundary layer and its relevance to the measurement of SST by airborne and spaceborne radiometers. Int.J.Rem.Sens., 5: 19.
- Saunders, R.W., Ward, N.R., England, C.F. & Hunt, G.E. (1982). Satellite observations of sea surface temperature around the British Isles. Bull.Am.Met.Soc., 63: 267.
- Saunders, R.W., Stowe, L.L., Hunt, G.E. & England, C.F. (1983). An intercomparison between radiation budget estimates from Meteosat-1, Nimbus-7 and TIROS-N satellites. J.Clim.App.Met., 22: 546.
- Zandlo, J.A., Smith, W.L., Menzel, W.P. & Hayden, C.M. (1982). Surface temperature determination from an amalgamation of GOES and TIROS-N radiance measurements. J.App.Met., 21: 44.

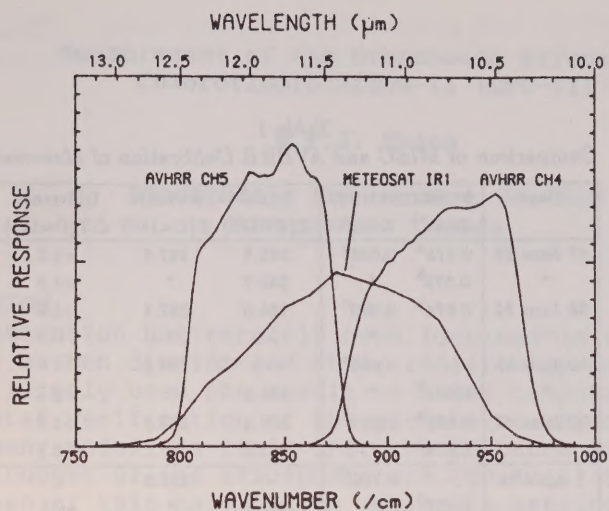


Figure 1
Spectral Response Curves of the Satellite Instruments

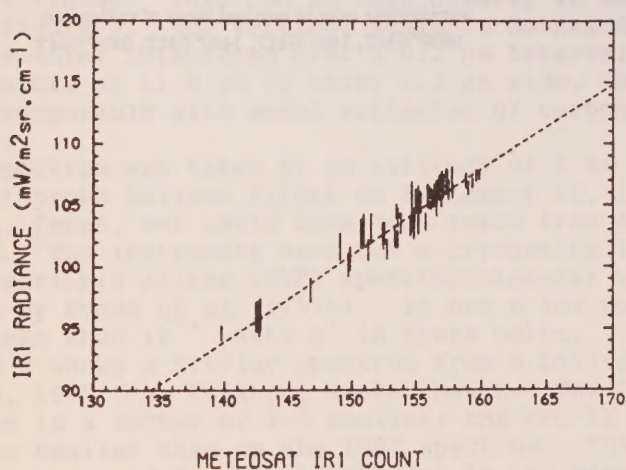


Figure 2
Results from 30 June 1982

Table 1
Comparison of MIEC and AVHRR Calibration of Meteosat

Date	MIEC Gain ^a	AVHRR Gain ^a	MIEC T(C=150)	AVHRR T(C=150)	Difference $\Delta T(C=150)$
27 June 82	0.673 ^a	0.695 ^c	285.5	287.5	+2.0
"	0.675 ^b	"	285.7	"	+1.8
28 June 82	0.674 ^a	0.690 ^c	285.6	287.1	+1.5
"	-	"	-	"	-
29 June 82	-	0.695 ^c	-	287.6	-
"	0.673 ^b	"	285.5	"	+2.1
30 June 82	0.672 ^a	0.697 ^c	285.4	287.7	+2.3
"	0.674 ^b	"	285.6	"	+2.1
1 April 84	-	0.709 ^d	-	288.9	-
"	0.715 ^b	"	289.4	"	-0.5
2 April 84	0.697 ^a	0.709 ^d	287.8	288.9	+1.1
"	0.713 ^b	"	289.3	"	-0.4
3 April 84	-	0.705 ^d	-	288.5	-
"	0.716 ^b	"	289.5	"	-1.0
4 April 84	-	0.712 ^d	-	289.2	-
"	0.715 ^b	"	289.4	"	-0.2
5 April 84	-	0.712 ^d	-	289.2	-
"	0.715 ^b	"	289.4	"	-0.2

^aunits are $\text{mW}/\text{m}^2 \text{sr.cm}^{-1} \text{ct}$.

superscripts refer to nominal times of calibration:

0600^aGMT, 1800^bGMT, 1400^cGMT, 0300^dGMT

Measurement of the Greenhouse Effect of Chlorofluorocarbon-11 (CFC-11)

W.F.J. Evans

Atmospheric Environment Service
Environment Canada

INTRODUCTION

Much attention has recently been focussed on the greenhouse effect of carbon dioxide and other radiatively active gases. This has largely been the result of model computations; little experimental verification of the greenhouse effect exists. Indeed, many modellers claim that the perturbations in the longwave budget of the atmosphere are too small to be measured. The purpose of this paper is to present a measurement of the change in downward flux due to chlorofluorocarbon-11 (CFC-11) from 1975-1982.

EXPERIMENTAL OBSERVATIONS

CFC-11 has a strong band at 847 cm^{-1} ($11.8\text{ }\mu\text{m}$) in the clear region of the long wave window from 10 to 12 micrometres. The window is limited below $10.2\text{ }\mu\text{m}$ by the $9.6\text{ }\mu\text{m}$ ozone band and above $12.5\text{ }\mu\text{m}$ by the $15\text{ }\mu\text{m}$ carbon dioxide band. Nitric acid has a large feature at $11.3\text{ }\mu\text{m}$. Water vapour has a continuum across the entire window. This can be seen clearly in the spectrum shown in Figure 1. The vertical scale is downward flux in watts per square meter integrated over a $0.2\text{ }\mu\text{m}$ interval. Since the CFC-11 feature at $11.8\text{ }\mu\text{m}$ is about $0.2\text{ }\mu\text{m}$ wide, this flux is directly comparable with model estimates of carbon dioxide flux increases.

This spectrum was taken at an altitude of 4 km from the ascent of a Stratoprobe balloon flight on September 22, 1982 from Palestine, Texas, but could have been taken from an aircraft just as easily. The instrument used was a cryogenically cooled circular variable filter (CVF) spectrophotometer which has been described by Evans *et al.* (1976). It has a low noise equivalent flux of less than 10^{-4} watts m^2 in these units.

Figure 2 shows a similar spectrum from a balloon flight on August 10, 1975 from Yorkton, Saskatchewan. The CFC-11 feature at $11.8\text{ }\mu\text{m}$ is a factor of 1.8 smaller; the CFC-12 feature at $10.9\text{ }\mu\text{m}$ is also smaller than on the 1982 spectrum. This is consistent with an increase of 7 percent per year in the mixing ratios of CFC-11 and CFC-12 (Malcolm *et al.*, 1982).

Comparison of the 1982 spectra clearly show that the CFC-11 feature has increased with time in a manner consistent with the observed increase in the concentrations of CFC-11 measured by gas chromatography. Figure 3 shows a similar spectrum measurement from the roof of the AES building in Toronto on January 15, 1984. The zenith angle was zero degrees in contrast to the balloon case when the zenith angle was 70 degrees. The same features

from CFC-11, CFC-12 and nitric acid can be seen. This spectrum has been scaled downwards by a factor of 2 to match the balloon altitude of 4 kilometres.

REFERENCES

- Evans, W.F.J., Lin, C.I. & Midwinter, C.L. (1976). The altitude distribution of nitric acid at Churchill. Atmosphere, 14(3): 172-179.
- Malcolm, K.W., Nien, K.O. & Sze, D.A. (1982). A 2-D model calculation of atmospheric lifetimes of N_2O , CFC-11 and CFC-12. Nature, 297: 317-319.
- Wardle, D.I. & Evans, W.F.J. (1976). The effect of freon usage on the global climate: the greenhouse freon effect. AES Internal Report No. APRB 40 X 8, January, 1976.

FIGURE 1.

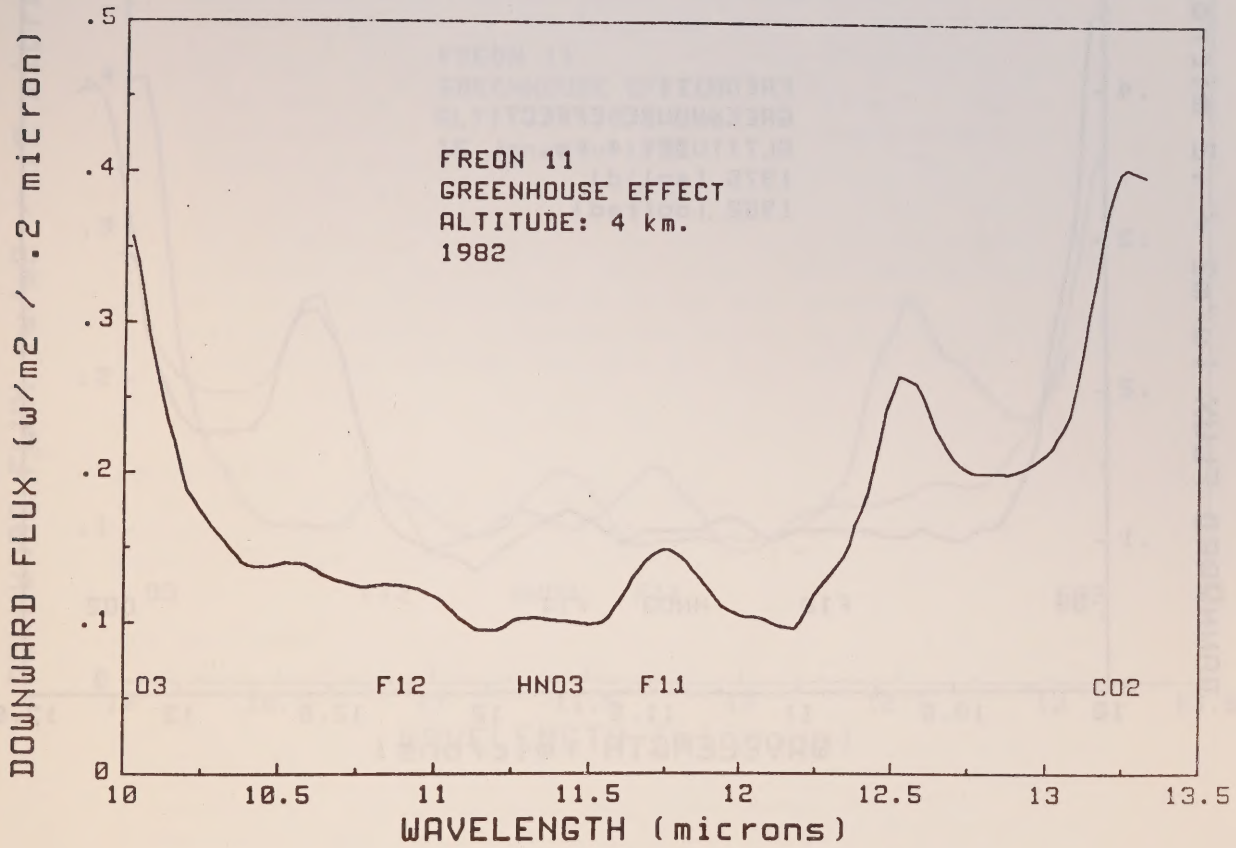


FIGURE 2.

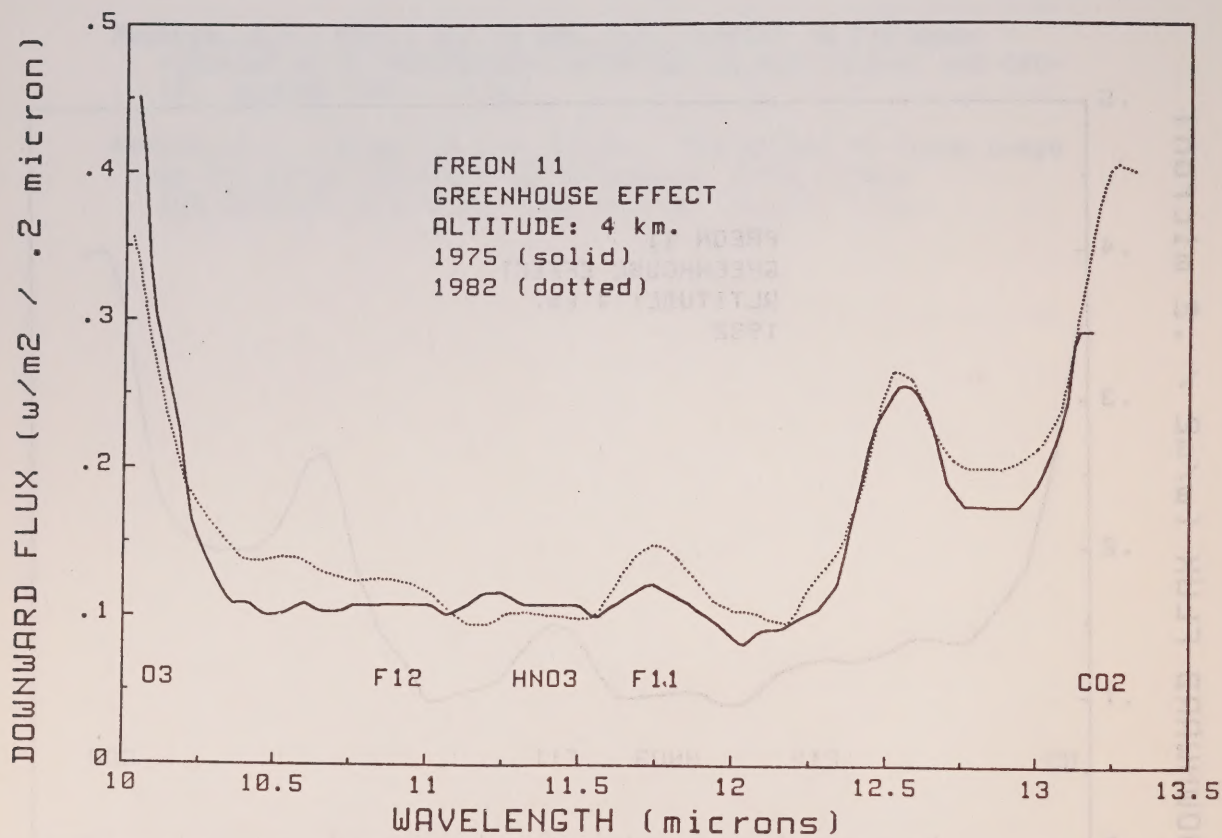


FIGURE 3.

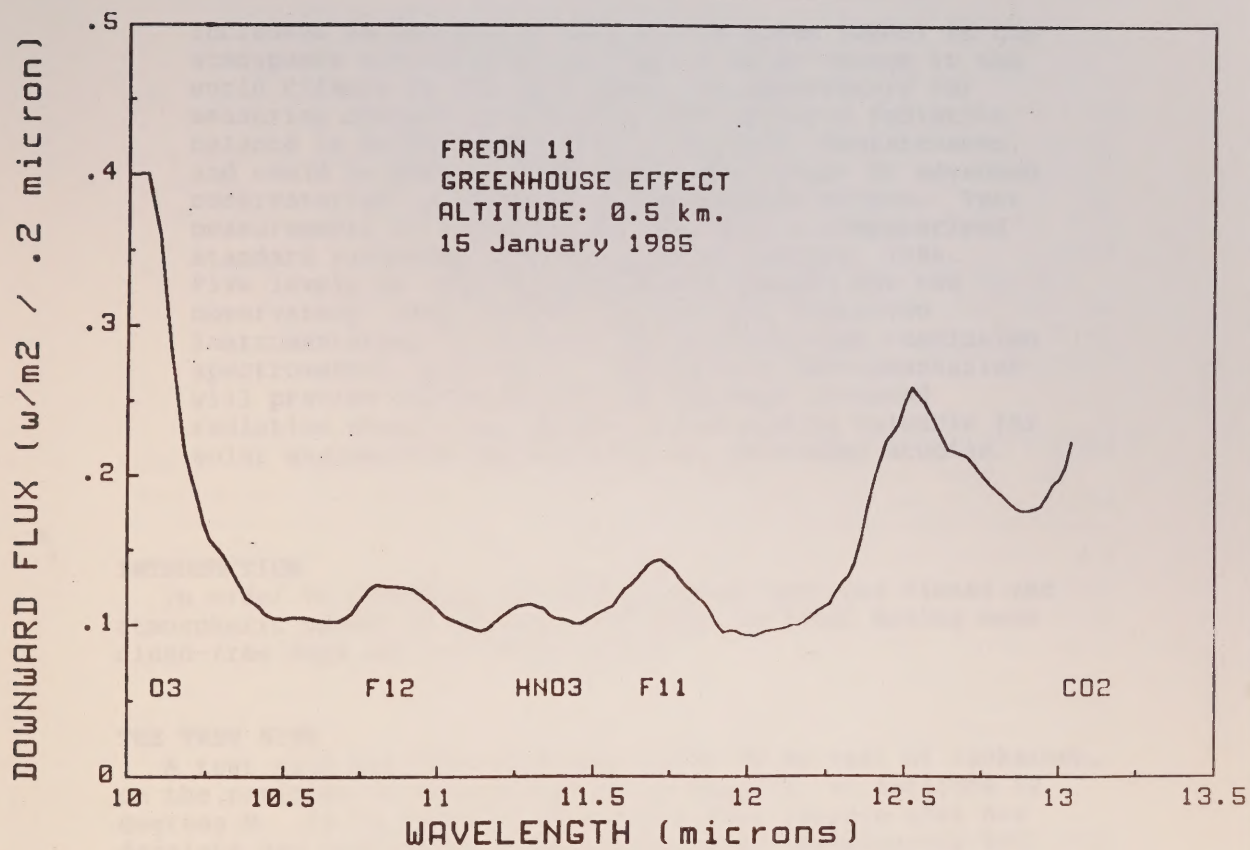
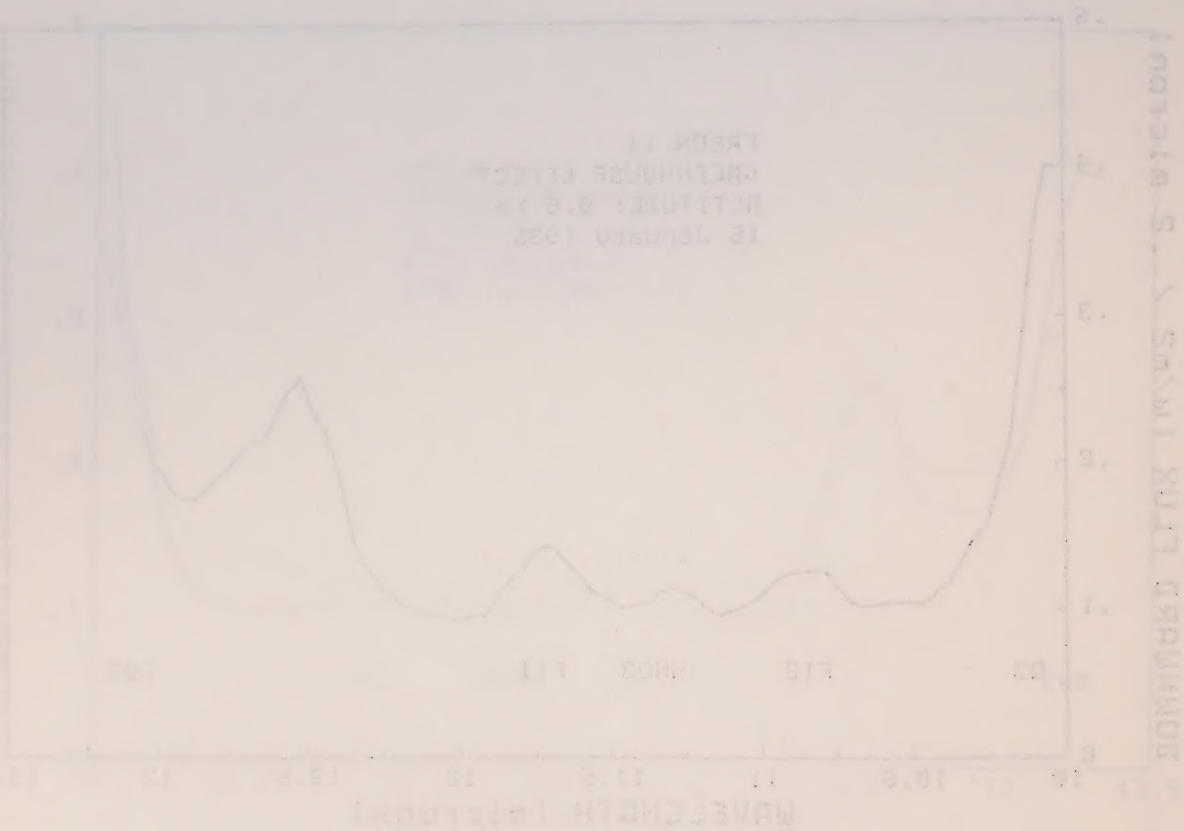


FIGURE 1



Proposal for a Radiatively Active Gas (RAGS) Observatory

W.F.J. Evans

**Atmospheric Environment Service
Environment Canada**

Abstract

Increases in the radiatively active gases (RAGS) in the atmosphere are expected to cause a major change in the world climate by the year 2050. An observatory for measuring changes in the long-wave infrared radiation balance is being established at Asquith, Saskatchewan, and would be part of a proposed world chain of advanced observatories monitoring the greenhouse effect. Test measurements to evaluate the site with a computerized standard radiation station began in January, 1986. Five levels of instrumentation are planned for the observatory, ranging from conventional radiation instrumentation in level 1, up to ultra-high resolution spectrometers in level 5. The level 1 instrumentation will provide Saskatchewan with the most advanced radiation station in Canada, and should be valuable for solar engineering applications and hydrology studies.

INTRODUCTION

In order to commence the monitoring of infrared fluxes and atmospheric gases, a suitable site must be found having many cloud-free days and low water vapour.

THE TEST SITE

A test site has been selected, about 20 km west of Saskatoon, on the prairies in western Canada at Asquith, at latitude 52 degrees N. It is situated on a clear flat terrain that has desolate dry conditions at an elevation of approximately 680 metres. It is located on top of a grassy knoll in the middle of a large farm. Radiation measuring instruments have been installed to test the suitability of the site. The control computers are housed in a trailer 50 metres away from the concrete piers which carry a global radiation pyranometer and a pyrgeometer for measuring long-wave, downward flux. The data are being compared with those from similar instruments on the AES rooftop observatory.

PLANNED FACILITIES

The ideal facility would be a building of 1000 square metres. The first storey would house the computer and calibration instruments, the second storey would contain the radiation instruments. The surrounding land would be planted with grass for 300 metres around the laboratory, which would be kept well mown in an attempt to control the ground albedo.

PROFILING CAPABILITY

There is a suitable site about 10 km south from which radiosondes and ozonesondes could be flown. The required profiling capabilities are summarised in Table 2. Larger balloons with up to 200 kg payloads can also be flown there. The scanning radiometer can be flown on a 50 kg payload to 40 kilometres. This instrument makes direct profile measurements of the downward flux from 6 to 14 μm at 1 km intervals. A second, similar instrument on the same payload could measure upwelling flux.

The measurement of profiles of water vapour, temperature, and IR flux have been identified in this report as essential ancilliary measurements to the ground spectral flux and transmission measurements.

LEVELS OF INSTRUMENTATION

The types of instrumentation that would be suitable for a RAGS observatory are shown in Table 1. Level 1 and 2 instrumentation comprises the conventional radiation station equipment. Level 3 instruments would allow low resolution measurement of infrared downward fluxes. Level 4 instruments would be required to monitor infrared atmospheric transmission and gases. The level 5 ultra high resolution instruments are still under development.

In addition, ozone and nitrogen dioxide will be monitored with two separate Brewer spectrophotometers. Aerosol optical depth will be monitored with an advanced sunphotometer, and eventually by Lidar.

STRATOSPHERIC MONITORING

The NASA plans a series of observatories for monitoring stratospheric change, and the RAGS observatory described here could form part of that chain.

This would require the addition of an ozone dial Lidar and some other instruments, but would otherwise have much of the capability of a NASA observatory for stratospheric change.

TABLE 1.

INSTRUMENTATION FOR A RAGS OBSERVATORY

1. Site with suitable terrain, clear horizon, clear sky

2. Building

Observatory building of 100 square meters eventually required, expanded in stages.

3. Equipment

- Level 1 - Pyrheliometer
- 2 - Global Pyranometer
- 3 - Diffuse Pyranometer

Level 2 - Direct Beam Filter Pyranometer (10 to 12 μm)
Filter global Pyranometer (long wave filter)

Level 3 - Low Resolution Scanning Solar and Emission Spectrometers (10 to 12 μm)

Level 4 - High Resolution Solar and Emission Interferometers (10 to 12 μm)

Level 5 - Heterodyne High Resolution Solar Spectrometer

TABLE 2.

RAGS GROUND OBSERVATORY AND PROFILE CAPABILITY

1. Small Balloons

- A. scanning radiometer 6 - 14 μm
- B. ozone sondes - temperature, ozone, humidity

2. Aircraft

- A. scanning radiometer

3. Vanscoy Launch site (10 km S. of the observatory)

- A. medium balloons - <200 kg payload
- B. NSBF large balloons

TABLE 1
 1. Size and number of the sample
 2. Size and number of the sample
 3. Size and number of the sample
 4. Size and number of the sample
 5. Size and number of the sample

1. Results

1.1. Results of the first experiment
 1.1.1. Results of the first experiment
 1.1.2. Results of the first experiment
 1.1.3. Results of the first experiment
 1.1.4. Results of the first experiment
 1.1.5. Results of the first experiment
 1.1.6. Results of the first experiment
 1.1.7. Results of the first experiment
 1.1.8. Results of the first experiment
 1.1.9. Results of the first experiment
 1.1.10. Results of the first experiment

1.2. Results of the second experiment
 1.2.1. Results of the second experiment
 1.2.2. Results of the second experiment
 1.2.3. Results of the second experiment
 1.2.4. Results of the second experiment
 1.2.5. Results of the second experiment
 1.2.6. Results of the second experiment
 1.2.7. Results of the second experiment
 1.2.8. Results of the second experiment
 1.2.9. Results of the second experiment
 1.2.10. Results of the second experiment

TABLE 2

1. Size and number of the sample
 2. Size and number of the sample
 3. Size and number of the sample
 4. Size and number of the sample
 5. Size and number of the sample

1. Results

1.1. Results of the first experiment
 1.1.1. Results of the first experiment
 1.1.2. Results of the first experiment
 1.1.3. Results of the first experiment
 1.1.4. Results of the first experiment
 1.1.5. Results of the first experiment
 1.1.6. Results of the first experiment
 1.1.7. Results of the first experiment
 1.1.8. Results of the first experiment
 1.1.9. Results of the first experiment
 1.1.10. Results of the first experiment
 1.2. Results of the second experiment
 1.2.1. Results of the second experiment
 1.2.2. Results of the second experiment
 1.2.3. Results of the second experiment
 1.2.4. Results of the second experiment
 1.2.5. Results of the second experiment
 1.2.6. Results of the second experiment
 1.2.7. Results of the second experiment
 1.2.8. Results of the second experiment
 1.2.9. Results of the second experiment
 1.2.10. Results of the second experiment

Infrared Limb Sounding of the Middle Atmosphere

John C. Gille

National Center for Atmospheric Research

INTRODUCTION

The advantages of observing the earth's limb are directly related to the geometry (Gille & House, 1971). Ray paths through the limb can be identified by the tangent point, the lowest point along the path. There is about 80 times as much atmospheric mass along a horizontal path through the limb as there is in a vertical path above the tangent point. Occultation (absorption) techniques take advantage of this effect, but the present discussion will be restricted to emission measurements. In this case, the emission by atmospheric gases will be observed against the cold background of space. This results in an optimal capability to measure the concentration of trace gases, and to extend temperature determinations to high altitudes. Because most of the opacity is concentrated just above the tangent point, the geometry also produces sharp weighting functions, which result in improved vertical resolution of the retrieved solutions.

The long paths through the atmosphere mean that even in relatively transparent spectral regions, the atmosphere can have appreciable opacity. This limits the ability to sound to low altitudes. The likelihood of clouds along the ray paths through the troposphere preclude sounding the troposphere on a regular basis, although clear lines of sight may occur sufficiently frequently to allow useful measurements to be made. Thus, the method is most useful for sounding above the tropopause.

Some observed radiances are shown in Fig. 1 taken from Bailey & Gille (1986). They are characterized by large values at low altitudes, where the atmosphere is opaque. Above this the signals fall steeply; this is the region that provides the best information about the atmosphere. At high altitudes, where the atmospheric paths are becoming nearly transparent, the signals drop to the noise level of the measurement. This ultimately sets the upper limit of useful sounding. Past experiments have obtained temperature and ozone retrievals to 60-70 km altitude.

The weighting functions for an infinitesimal field of view (FOV) are quite sharp and peaked. Even after convolution with a 2 km FOV, the weighting functions have half widths at half maximum of 4.5 kilometres. This allows atmospheric variations with wavelengths of several km to be retrieved. The highest resolution attainable depends on the amplitude of the signals, and the noise level. It is clear that to take advantage of the high inherent resolution of the geometry, a narrow FOV is needed. This implies that small signals need to be measured with high precision and accuracy.

INSTRUMENTATION

An instrument that shows how these and other requirements may be met is that of the Limb Infrared Monitor of the Stratosphere (LIMS) experiment that flew on Nimbus 7. The experiment has been described in detail by Gille and Russell (1984). A scan mirror brought radiance from a range of altitudes at the earth's limb through a folded telescope having an 18 cm primary mirror to a focus, where it was chopped. The beam was then re-collected and directed through an ambient temperature window, relay mirrors (152K) and interference filters (65K) onto HgCdTe detectors (65K). LIMS had six channels to measure radiances emitted by CO₂ (2), O₃, HNO₃, H₂O, and NO₂; their parameters are given in Table 1.

A large part of the engineering was involved with the solid cryogen package that maintained these cold temperatures, which were necessary to obtain the low noise levels needed. The primary cryogen was solid methane (CH₄) at 65K, the life of which was extended by a protective shell of solid ammonia (NH₃) at 152K. The amount of the cryogens limited the experiment to a seven month lifetime.

In the retrieval, it is necessary to know the spacing of the radiance samples very accurately. This was achieved by having a constant angular velocity of the mirror, and uniform sampling frequency. It was critical to have good pre-flight measurements of such instrumental characteristics as the FOVs of the different channels, their spacing relative to each other, and the spectral response functions. Also, the retrieval requires knowledge of the absolute radiance. This was accomplished with in-flight calibration, looking at cold space and a small black body (308K) whose characteristics had been carefully calibrated in the laboratory.

INVERSION METHOD

The procedure is to solve for the temperature by inverting the radiances emitted by CO₂, because the CO₂ mixing ratio is known, then using the temperature with the radiances emitted by other gases to solve for their mixing ratios. The retrieval is based on the physics, and because the atmosphere is required to be in hydrostatic equilibrium, the problem of temperature retrieval, as it is usually formulated, is very non-linear. The solution therefore requires iteration, which in turn demands rapid calculation of the transmittance. It is essential to have a transmittance model that is accurate and fast over the spectral intervals used, which in the past have been quite broad.

Note that the rapid fall off of the radiances with altitude in the important altitude region means that the pointing direction of the line of sight must be accurately known. The distance from the spacecraft to the limb is typically 3000 km or more; small errors in spacecraft altitude or attitude will lead to unacceptably large errors in pointing direction. Even if the absolute pointing direction were known, however, this would not

be sufficient, because the retrieval requires the atmospheric density to be known. Fortunately, it is possible to derive pointing information from the measured radiances. The physics of the two-color approach is described in Gille and House (1971); subsequent work has used this basic principle, although the implementation has differed.

A fast inversion method suitable for implementation on a small computer has been described by Bailey and Gille (1986). In this, the transmittance information is included in emissivities, which are parameterized in a rather simple way. A more elaborate algorithm is described by Gordley and Russell (1981).

RESULTS

Examples of retrievals of temperature and nitric acid are presented in Figure 2. Note that the temperature (and ozone) solutions extend from 100 mb (about 15 km altitude) to 0.1 mb (about 64 km), while the nitric acid extends only to 2 mb, or about 45 km, due to the weaker signal levels. The other two points illustrated by the temperature solution are the agreement with the conventional data (radiosondes and rockets), and the good vertical resolution that can be seen in the retrieval and the rocket sounding. The nitric acid also shows good agreement with conventional data. A summary of the calculated error budgets, and the agreement with the comparison data, is contained in Table 2. These data have been analyzed to give global maps at a number of middle atmospheric pressure levels. These and latitude-altitude cross-sections are providing an enormous increase in our knowledge of the chemistry and dynamics of the middle atmosphere.

APPLICATIONS

Three satellite-borne IR limb scanners have returned major amounts of data to date. These are the Limb Radiance Inversion Radiometer or LRIR (described by Gille *et al.*, 1980a,b); LIMS, and the Oxford University Stratospheric and Mesospheric Sounder (SAM, see Wale & Peskett, 1984 & Rodgers *et al.*, 1984). The Upper Atmospheric Research Satellite (UARS) will have an improved SAMS (ISAMS) and the Cryogenic Limb Array Etalon Spectrometer (CLAES), an instrument with much higher spectral resolution (about 0.2 cm) in nine narrow spectral intervals. A closely related instrument is the Microwave Limb Sounder (MLS), which employs many of the same principles.

CONCLUSIONS

Infrared limb scanning has many inherent advantages, although the retrieval problem for temperature is highly non-linear. It is also technically demanding. With careful attention to the instrumental aspects of the technique, very good results have been obtained which are opening up our understanding of the

middle atmosphere. There are still questions about the optimum methods of parameterizing the transmittances and of doing the retrievals, although several approaches have been used successfully. These successes have led to the widespread application of the technique for future measurements of the important variables in the middle atmosphere.

ACKNOWLEDGEMENTS

National Center for Atmospheric Research is funded by the National Science Foundation.

REFERENCES

- Bailey, P.L. & Gille, J.C. (1986). Inversion of limb radiance measurements: an operational algorithm. J. Geophys. Res. 91: 2757-2774.
- Gille, J.C. & House, F.B. (1971). On the inversion of limb radiance measurements I: temperature and thickness. J. Atmos. Sci., 28: 1427-1442.
- Gille, J.C. & Russell III, J.M. (1984). The limb infrared monitor of the stratosphere: experiment description, performance, and results. Geophys. Res. 89: 5125-5140.
- Gille, J.C., Bailey, P.L. & Russell III, J.M. (1980a). Temperature and composition measurements from the LRIR and LIMS experiments on Nimbus 6 and 7. Phil. Trans. Roy. Soc. Lond., A, 296: 205-218.
- Gille, J.C., Bailey, P.L., Craig, R.A., House, F.B. & Anderson, G.P. (1980b). Sounding the stratosphere and mesosphere by infrared limb scanning from space. Science, 208, 397-399.
- Gordley, L.L. & Russell III, J.M. (1981). Rapid inversion of limb radiance data using an emissivity growth approximation. Appl. Opt., 20: 807-813.
- Rodgers, C.D., Jones, R.L. & J.J. Barnett (1984). Retrieval of temperature and composition from Nimbus 7 SAMS measurements. J. Geophys. Res., 89: 5280-5286.
- Wale, M.J. & Peskett, G.D. (1984). Some aspects of the design and behavior of the stratospheric and mesospheric sounder. J. Geophys. Res., 89: 5287-5293.

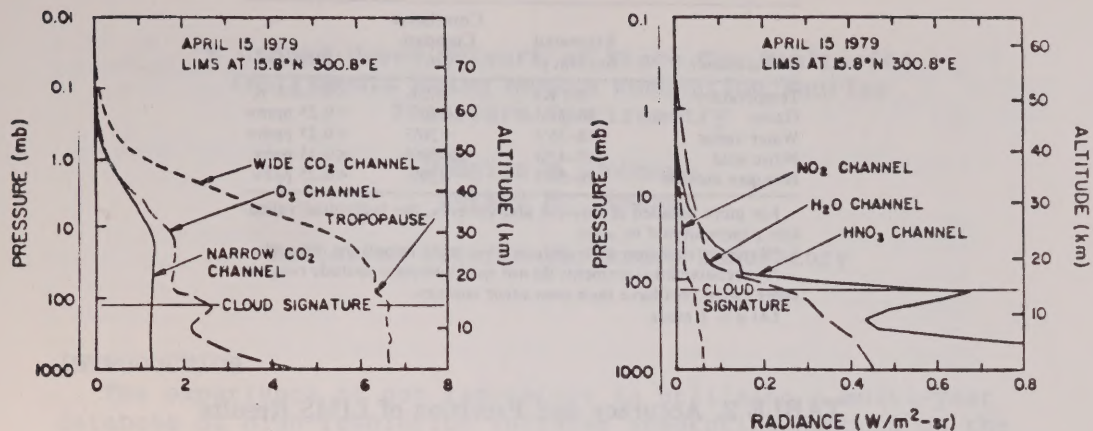


FIGURE 1.

Limb Radiance Profiles Measured By LIMS

Channel	Emitting Gas	Bandpass % Relative Response Points, cm ⁻¹	Field of View at Limb, km		Noise Equivalent Radiance, (W/m ² sr)
			Vertical	Horizontal	
1	NO ₂	1560-1630	3.6	28	0.00055
2	H ₂ O	1370-1560	3.6	28	0.0023
3	O ₃	926-1141	1.8	18	0.0037
4	HNO ₃	844-917	1.8	18	0.0015
5	CO ₂ W	579-755	1.8	18	0.0055
6	CO ₂ N	637-673	1.8	18	0.0014

TABLE 1.

Characteristics of LIMS Channels

Parameter	Estimated Accuracy*	Correlative Comparison†	Precision
Temperature	≤ 2 K‡	≤ 2 K	$< 0.2-0.6$ K
Ozone	16-41%	$< 10\%$	< 0.25 ppmv
Water vapor	18-36%	$< 20\%$	< 0.25 ppmv
Nitric acid	17-45%	20-50%	< 0.15 ppbv
Nitrogen dioxide	20-50%	$\leq 20\%$	< 0.25 ppbv

For more detailed discussion and caveats, the individual validation papers should be seen.

*Range is variation with altitude over most important intervals.

†Correlative measurements do not span complete altitude range in some cases, and have their own error sources.

‡At $p \approx 1$ mbar.

TABLE 2. Accuracy and Precision of LIMS Results

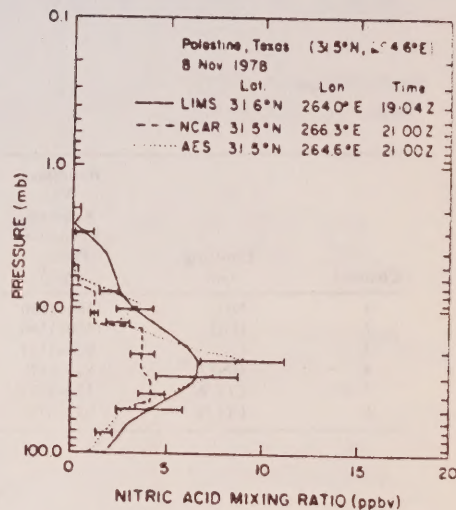
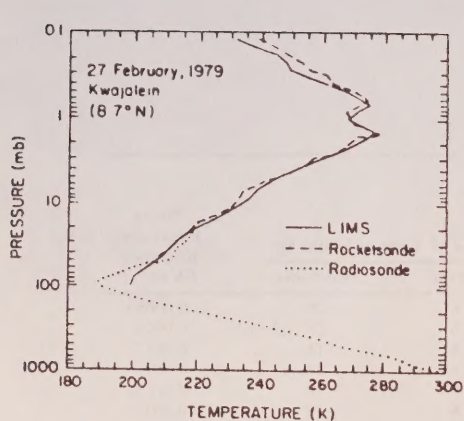


Fig. 2 Examples of LIMS retrievals and their comparisons to in-situ measurements.

**A Ground-Based Network of Trace Gas Monitoring
Instruments Using Medium Resolution Fourier
Transform Spectrometry**

**Douglas W. Johnson
Gerald M. Stokes**

Battelle, Pacific Northwest Laboratory

INTRODUCTION

The experience of our laboratory in utilizing a multi-year database of high-resolution infrared absorption spectra of the earth's atmosphere has led to several advances in the understanding of seasonal and secular variations of trace gases. Included in species measured from the Kitt Peak National Observatory (KPNO) database are CO_2 , CH_4 , HCl , HF , NO and NO_2 . In addition, a number of other studies have utilized the same dataset (Zander and Stokes, 1982; Rinsland *et al.*, 1984; Flaud *et al.*, 1983). Key features of the Kitt Peak dataset are:

KPNO FTS/McMath Solar telescope combination yields high resolution (better than 0.01 cm^{-1}) and high signal-to-noise (typically 10^3 in the continuum),

Data in the $1\text{-}5 \text{ }\mu\text{m}$ region collected two days per month (weather permitting) over the period from late 1978 to December 1985.

Spectra obtained at 10, 5 & 3 airmasses in the morning and afternoon as well as at minimum airmass.

Additional spectra obtained at irregular intervals in the $8\text{-}12 \text{ }\mu\text{m}$ region.

The original goals in collecting this data were to enable interpretation of much older, extremely low resolution data in a project for the Carbon Dioxide Research Office, DOE. This dictated the use of $1\text{-}5 \text{ }\mu\text{m}$ window to utilize the CO_2 band at 2.6 micrometers. This region additionally contains features of CH_4 , HCl , HF , NO and NO_2 , subsets of which have also been examined. As interest in other trace gases and their climatic impact arose, data in the $8\text{-}12 \text{ }\mu\text{m}$ band was obtained as the Kitt Peak instrumental configuration schedule allowed. This latter data is clearly best-suited for study of the so-called "greenhouse" issues because it is actually a direct measure of the transparency of the earth's atmosphere at the crucial wavelengths for planetary cooling.

While the dataset has proven very valuable for monitoring of a number of trace gases, there are significant drawbacks associated with the current dataset. Chief among these are:

A single site for all data collection at Kitt Peak, Arizona.

Relatively expensive costs associated with data collection and processing at the site, mostly stemming from the sophistication of the instrumentation and the manpower necessary for operation.

Lack of detailed vertical profile information.

This document outlines an approach to rectifying some of these shortcomings by developing and deploying a north-south chain of remotely operating Fourier Transform Spectrometers (FTS) designed to collect absorption spectra on a nearly continuous basis. Each unit would contain: fore-optics; a medium resolution FTS; and a data acquisition and recording system.

A fully deployed network would utilize 8-12 units distributed approximately equidistant in latitude over as wide a range as practical.

The basic mode of operation is the collection of absorption spectra of the atmosphere using the sun as a broad band background source. Observations during the course of a day result in a range of airmasses being observed. This airmass-dependent data results in atmospheric curves-of-growth (column density as a function of zenith angle) for each molecule detected. An inversion procedure or modeling-fitting technique can then be used to extract the equivalent overhead column density and limited information on the vertical profile of the molecule involved.

PROGRAM OBJECTIVES

Based on our experience with the Kitt Peak database, a multi-latitude, multi-year database of medium resolution spectra would be useful to the atmospheric science community in a number of ways. Among these are:

Seasonal and secular trend data for important atmospheric constituents, particularly climatically active compounds absorbing in the 8-12 μm region.

Ground-based corroborative data (ground-truth) for satellite-based trace gas information.

Atmospheric aerosol loading information from either the FTS spectra or simultaneously obtained broadband data.

Latitudinal dependence for all quantities measured.

Key features of the program include high confidence in the technique. Infrared absorption spectroscopy is a well-understood and mature discipline which enjoys wide use by the atmospheric science community. The program is also relatively low in cost when compared to more exotic technologies such as lidar, and balloon-borne or satellite-based instruments. Further, the establishment of a long-term database of high-quality data will be particularly sensitive to the multi-year trends that are very difficult tasks for most current sampling and measurement programs. The data will, of course, be archived in a form easily accessible for later analysis. The option of re-analyzing a dataset with entirely different objectives can be extremely valuable and data archiving should be performed with this in mind.

Our laboratory has recently completed a program, managed by Gerry Stokes, for the Carbon Dioxide Research Office of DOE in which data obtained by the Smithsonian Astrophysical Observatory during a 50-year program was used to determine the atmospheric abundance of CO_2 in the atmosphere during that period. The data was originally obtained to determine if the solar constant was indeed constant. The atmospheric parameters extracted by the Batelle PNL program were, in effect, the noise in the original experiment.

The accuracy and precision possible with the FTS technique can be roughly estimated from existing spectroscopic data and experience with extracting similar values for a variety of molecules. Of course these parameters depend heavily on instrument design and data analysis protocols (e.g. temporal resolution desired, use of redundant line measurements, etc.) but a general indication of achievable results is useful for experiment assessment and possible modification. Better estimates of the ultimate capability of such a network can be determined from a performance specification for the instrument (e.g. resolution, sensitivity, observing protocol, etc.) by coupling this data with synthetic spectral routines and performing model analyses on the resulting data.

Table 1. lists the individual molecules expected to be accessible with this technique. Cognizant of the preliminary nature of the instrument design, we have grouped the molecules which can be detected and measured with reasonable FTS designs into three categories (designated A, B and C) reflecting the general quality of the measurements expected. These preliminary estimates of the effectiveness of the technique (by assigning each molecule to a group) are based on past experience with higher resolution data from the Kitt Peak data base.

TABLE 1.

Molecules Measurable with Ground-Based FTS

Molecule	Group	Wavelength Region μm
CO_2	A	9-11
H_2O	A	?
O_3	A	?
N_2O	A	?
CH_4	A	?
CO	B	?
NH_3	B	?
HNO_3	B	11.5
HCl	B	3.42
HF	B	2.48
NO	C	?
NO_2	C	?
CCl_3F (F-11)	B	11.8
CHCl_2F_2 (F-12)	B	10.5-11.5
CHClF_2 (F-22)	C	12.2-12.5

The quantity of data available for analysis will be very large for each site because the instrument can be in essentially continuous operation from sunrise to sunset. Each spectrum can be analyzed for a number of lines belonging to one molecule, providing additional measurements of the column density and ancillary information on atmospheric temperature effects.

Successive days of observations can also be combined for detecting longer term trend information. These averaging techniques are an effective and powerful means of increasing the precision of trend analyses.

A major concern when analyzing data of relatively low resolution is the presence of undetected, blended features that result in contaminated data. Several approaches can be used to minimize these concerns. Among them are to:

Carefully assess potential contamination with line compilations, exercising caution due to the incompleteness of these lists.

Utilize high-resolution data to identify and possibly correct for contaminating features.

Extend the analysis to a number of spectral features, some of which may be contaminated but almost certainly not with the same temporal or spatial variability characteristics.

Table 2 summarizes the groups and indicates the anticipated accuracy and precision for individual measurements and trend estimates. As noted above, these estimates are provisional and will, of course, depend on the design details of the FTS instrument.

TABLE 2.

Estimated Measurement Uncertainties

Group	Accuracy	Precision	Trend Precision
A	$\leq 10\%$	5%	$0.5-1\% \text{ yr}^{-1}$
B	20%	10%	$1-10\% \text{ yr}^{-1}$
C	$\geq 50\%$	$\leq 50\%$	$\geq 20\% \text{ yr}^{-1}$

The group A molecules are the easiest to measure and should result in the best absolute values and trend estimates. Anticipated accuracies are better than 10% and precision maybe about half that value. Group B contains molecules that are clearly detectable and will yield some information on trend, although in general the results will be less accurate than that obtained for group A. Group C represents molecules that may be detectable with special experimental arrangements or through sophisticated averaging or analysis techniques that render trend detection and determination more problematic.

The following sections treat the potential uses of this data in more detail. It should be clear that the value of the data derives from the time history and latitudinal distribution, enabling the analysis and assessment of a different regime of atmospheric composition issues than typically envisioned.

Seasonal and Secular Trend Measurement

One of the more difficult atmospheric measurements to make is the variability of atmospheric constituents on a several year to decade-long time scale. Measurement programs have tended to be rather short in time and usually quite narrow in scope. Recent exceptions to this trend include coordinated campaigns to either measure the same compounds with different techniques (Balloon Intercomparison Campaign-1 and 2; Ozone Intercomparison Campaign) or to measure many different constituents and parameters simultaneously within the same region and time. The former class of experiment is useful for intercomparison of instruments and techniques, while the latter is designed for establishing well-characterized datasets for analysis of interrelated chemistry, meteorology and model testing/validation.

Not addressed by these measurement campaigns is the longer term perspective of atmospheric variability. This aspect of the current situation is reflected in the current state of atmospheric measurements by the CO₂ data set collected by Dave Keeling at Mauna Loa. The trends detected in these measurements triggered an interest in climatic effects that continues today. The importance of the original long-term, high quality measurements is widely acknowledged to be an outstanding example of good experimental science, quickly focusing the study of atmospheric CO₂ effects on environment and consequences instead of verification of data and measurement techniques.

Ground Truth Support

One of the major hurdles facing the effective use of satellite-based trace gas data is validation and verification of the derived results. While this problem exists for shuttle-based instruments with experimental runs of 1 week, it becomes particularly acute for instruments remaining in orbit over extended periods of time. Degradation of instrument optics, changes in detector response and evolution of the overall instrument response function must be carefully monitored, measured and corrected before the data can be relied upon for the multi-year time scales being considered here.

Ground-based data, obtained with instruments easily accessible and maintainable, can provide valuable reference data for calibrating the longer-term satellite trends and fluctuations. The existence of the north-south chain is crucial in this respect, since it provides the most important dimension of global atmospheric variability next to vertical profiles - latitudinal dependence.

Atmospheric Aerosol Measurements

Additional measurements on the loading of the atmosphere with aerosols could be readily obtained. In general the tropospheric contribution is considerably larger and more variable than that from the stratosphere because of the population and agriculture -related activities. We have considerable success here at Batelle PNL in separating these effects, particularly during times of high stratospheric contributions following major volcanic events.

The most straightforward method of obtaining these data would be an auxiliary instrument in the unit making direct photometric measurements of the solar irradiance in the visible and near infrared regions of the spectrum. These data form the basis for inversion procedures to determine aerosol opacities (stratospheric and tropospheric can be separated in multi-year data sets) and can also be used to investigate questions of size distribution.

Latitude Dependence

On time scales longer than a few weeks, the earth's atmosphere is well mixed longitudinally. This suggests the use of instrumented sites at discrete latitudes as an effective means of sampling the latitudinal dependence of the measured concentration data. Optimum spacing is probably about every 15° in latitude resulting in a maximum of thirteen instruments for pole-to-pole coverage. Geographical and logistic requirements may reduce this number.

Vertical Profiles

Our experience, particularly in the BIC-1 and 2 experiments, indicates that ground-based solar absorption data contains significant vertical profile information provided airmass coverage is obtained at high zenith angles. The majority of the information resides in the curve of effective airmass (or column density) versus zenith angle, and is due to the geometric effect of the vertical profile.

The quality of the data (i.e. the vertical dimension and placement of weighting kernels) is not clear at present, but the possibility of extracting 2-4 layers with greatest retrieval accuracy in the troposphere/lower stratosphere appears possible. Shaffer & Shaw (1983) describe the situation well and indicate that a requirement for meaningful retrievals, even for these minimal vertical resolutions, is high signal-to-noise ($\sim 10^4$) data.

INSTRUMENT DESIGN

Any experiment and associated experimental design should be approached from the direction of the results desired asking, What will the data be used for and how will the analysis be done? This results oriented-approach will do much to ensure that instrument design, data analysis collection and associated analysis tools are considered early on in the project. In addition, a number of specific objectives for a greenhouse gas monitoring effort must be incorporated for a successful program design and implementation. A number of these issues are discussed in the following paragraphs.

The basic instrument should be as portable as possible for ease of siting in remote locations. The enclosure should be climate-controlled for increased reliability of the instrumentation, particularly the FTS electronics and computer-related items such as disk drives and tape units. Solar viewing access should be unobscured from sunrise to sunset to maximize limits in observed airmass values.

Our group at Battelle's Pacific Northwest Laboratory (PNL) has operated, for nearly a decade, a network of auroral scanning instruments distributed across the United States and into Canada which conform closely to the requirements noted above. The basic enclosure is a heated, air conditioned pickup camper back with a hemispherical viewing bubble on the top. The unit is transported

to the selected site with an ordinary pickup truck and unloaded onto a concrete pad to which adequate power supplies have been routed. A weekly visit by a local assistant is sufficient for tape exchange and preventive maintenance. More extensive repair/reprogramming work is performed during approximately yearly site visits.

Hardware Design

The remote FTS instrument contains three major subassemblies plus the enclosure and external power supplies. These are outlined briefly in the following sections.

Optical System

The optical system must be capable of bringing a collimated beam of solar radiation of suitable size to the entrance aperture of the FTS itself. The assembly must accurately track the solar center from sunrise to sunset. This can be accomplished either by calculation of the direction to the solar disk, or more likely, an active quadrant detection system to actively track the sun.

The optics must be either enclosed in a weatherproof housing through which observations can be made at the appropriate wavelengths, or alternatively, the unit must be able to detect inclement or potentially damaging weather conditions and stow/shield optics adequately.

FTS Assembly

The heart of the instrument is the FTS assembly. Adaptation of commercial units to this task is likely and the provision of a generally benign environment via the climate-controlled enclosure will significantly ease system development and ruggedization. Detailed specifications for the FTS are not considered here.

Data Acquisition and Recording

An essential ingredient to operate an FTS instrument in the manner described will be a local computing system capable of the carrying out the tracking and electronic control functions associated with the data acquisition. The same system will serve to store the intermediate results to disk and perform preprocessing of the data as needed. Nighttime hours provide a logical time for these tasks, excepting for summer operation at high latitudes. Subsequent transfer to magnetic media for collection and transmittal to central data center by the local support person will also be necessary.

Data Analysis Issues

Much of the routine preprocessing of the FTS data can be performed by the local computer to relieve the burden on the central computing facility. The nature of the pre-processing should, of course, be limited to that which does not degrade the temporal or frequency resolution of the data unnecessarily. A primary goal of the preprocessing is to minimize the data volume to be recorded and thus extend the time of unattended operation as long as possible.

Once the data is received at the central data center a number of software tools exist to efficiently analyze the large amount of spectral decomposition routine developed at Kitt Peak National Observatory by James Brault and KPNO staff. The package iteratively fits a set of Voigt profiles to a spectrum, minimizing the residuals between the observations and calculated spectrum.

Also available is the Air Force Geophysical Laboratory package, FASCOD2. This is a spectral synthesis routine integrated with the AFGL spectral database and often forms the basis for synthetic spectral line fitting routines. The routines allow specification of a number of constraints including:

Arbitrary atmospheric models.

Vertical profiles of trace gases.

Fully specified paths through the atmosphere.

The resulting spectrum, based on the parameters from the linelist, can be plotted for further analysis or used as input values for an iterative fitting procedure to match the observational data.

CONCLUSIONS

A project to develop a network of remotely operating FTS instruments capable of obtaining absorption spectra of the earth's atmosphere is well within current capabilities and would have significant advantages over existing data collection networks. The determination of seasonal and secular concentration trends over multi-year time scales for a wide variety of atmospheric molecular constituents is the primary goal of this project. Ancillary contributions in the area of ground truth for satellite observations and the possibility of associated aerosol measurements would provide much information on the latitudinal transport of volcanic related aerosols.

After several years of successful operation, the data set would make a fundamental contribution to the area of global atmospheric constituent measurements that would serve well the analysis and interpretation of later shuttle and free-flying EOS instruments.

REFERENCES

- Flaud, J.M. & Camy-Peyret, C. (1983). First infrared measurements of atmospheric NO_2 from the ground. Geophys.Res.Lett., 10(1): 35-38.
- Rinsland, C.P., Boughner, R.E., Larsen, J.C., Stokes, G.M. & Brault, J.W.(1984). Diurnal variations of atmospheric nitric oxide: ground-based infrared spectroscopic measurements and their interpretation with time-dependent photochemical model calculations. J.Geophysical Res., 89: 9613-9612.
- Shaffer, W.A. & Shaw, J.H. (1983). Resolution of vertical mixing-ratio profiles of atmospheric constituents retrieved from solar spectra. Appl. Optics, 22: 2977-2983.
- Zander, R. & Stokes, G.M. (1982). Spectroscopic detection of acetylene and ethane in the earth's atmosphere through ground-based infrared solar observations. Comptes Rendue d' Academie Scientifique de Paris, 295: 585-586.

Umkehr Observation of the Ozone Layer, and Infrared Measurements of Stratospheric and Tropospheric Minor Constituents

Pierre Marché

Université de Reims

INTRODUCTION

The Dobson 85 spectrophotometer was automated at Boulder in 1983, and has been installed at the Observatoire de Haute-Provence since August 1983. The first Umkehr profile was obtained on the 3rd September 1983 (Fig. 1). Since then Umkehr observations have been taken every day at sunrise and sunset, when the meteorological conditions allow.

The raw data are sent to NOAA at Boulder, and to AES at Toronto, where the ozone profiles are retrieved with standard programmes. For the period 3rd September 1983 to the end of April 1985 there are a set of 450 ozone profiles, corresponding to an annual average of 270 profiles.

Figure 2 shows the total temporal variability amplitude (Sept 1983-Apr 1985) in each Umkehr layer. The maximum variability is seen in layer 2: this is explained by the negative correlation between ozone concentration and the height of the tropopause (which is very variable).

Figure 3 shows the relative variability for ozone in each Umkehr layer versus days. The mean is drawn as an horizontal in front of each layer number, the scale is taken as follows:

n + 1	-----	(mean of layer n) x 2
n	-----	(mean of layer n)
n - 1	-----	0 for layer n

The temporal ozone variability in the layers 0 to 7 (0-35 km) show that there are two minima (Oct-Nov 1983 and Oct-Nov 1984), and two maxima (Mar-Apr 1984 and Mar-Apr 1985) which are due to the annual cycle (see, Figs. 5 & 6). The ozone variability in layers 8 to 12 does not show such correlation with the annual cycle.

Figure 4 shows (same scale) the variation in each Umkehr layer and the total ozone variation versus time for two comparable periods (Sept 1983-April 1984 and Sept 1984-Apr 1985). A strong correlation exists between total ozone and layers 0, 1, 2 constituents is evident.

The total ozone variation is shown on Figs. 5 and 6. We have used a SISAM-type spectrometer for the infrared determination of total ozone above the OHP, the spectral resolution is 0.018 cm^{-1} . Figure 7a shows a synthetic spectrum calculated for a zenith angle equal to 31.9 degrees and for a wavenumber from 2083.75 to 2085.15 cm^{-1} . Figure 7b shows a spectrum recorded at OHP for the same zenith angle, the strong lines on both sides of each

spectrum result from carbon dioxide absorption. Fig. 7c shows an adjustment between calculated and observed spectra in a spectral range ($2084.3\text{--}2084.7\text{ cm}^{-1}$) where all absorption lines result from atmospheric ozone absorption.

Figure 8 shows the day to day total ozone variation measured by both Dobson and IR instruments during the MAP/GLOBUS campaign.

The agreement between both instruments is good, the difference shown on the 13th September can be explained by TOMS ozone map (Fig. 9) which shows a difference between OHP-St. Michel and OHP-Mt.Chiran.

The R1 line of the fundamental band of HCl located at 2925.898 cm^{-1} has been recorded during MAP/GLOBUS Campaign (Fig. 10). On the 13th September 1983, a set of 25 spectra was recorded between 80 and 90 degrees zenith angle. This enabled us to plot a zenith curve and to deduce information about the vertical concentration profile of HCl shown on Fig. 11. On the same figure are also plotted the profiles fitting the Jungfraujoch observations made by Zander, and the profile obtained by Karcher on-board a Caravelle aircraft.

Figure 12 shows a day to day comparison of total amount of HCl obtained at OHP and at Jungfraujoch.

The following figures show the other molecules which are occasionally recorded at OHP by the IR spectrometer.

INFRARED

By infrared high resolution spectroscopy, we may derive total column density and vertical concentration profile (even from the ground). We observe a great number of individual lines of many molecules and choose for ozone (for example) a spectral region where we are sure to avoid problems of interference with other molecules. The infrared spectra is not affected by aerosols or diffusion (large values of λ). If we know the molecular parameters which are derived from laboratory measurements and calculations, all the physics used to obtain results on atmospheric concentration is very well understood. Two results may be obtained:

1. Total column density

Total column density is directly obtained from the equivalent width of the considered line(s). For this, we must know the wavenumber(s), with the best accuracy (of the order of 10^{-7}) to avoid interference problems, and the line strength $S(\text{To})$. They are observed and calculated in laboratory. We also derive from calculations the lower energy level E'' for the considered transition(s). The intensity of the line may be calculated at various temperatures, with the relation:

$$S(T) = S(T_0) \exp \left[- 1.439 E'' \left(1/T_0 - 1/T \right) \right]$$

E'' being expressed in cm^{-1} .

Then, having made an initial guess for the vertical profile (see below), we derive the total column content. This has been done for many species, e.g., O_3 , HCl , HF , H_2CO , ...

2. Vertical Concentration Profile

The line shape is a Voigt function, that is to say a convolution of the Doppler effect (Gaussian curve) and the pressure effect (Lorentzian curve). This last one may be written:

$$\alpha \text{ (cm}^{-1}\text{)} = \alpha_0 \text{ (cm}^{-1}\text{/atm)} \cdot P \text{ (atm)}$$

The α_0 (air broadening coefficients) are measured in laboratory.

Then the line shape is directly a function of the pressure, (i.e. of the altitude). Observing the true line shapes we derive the vertical concentration profile by the inversion method. The only assumptions are: (a) the vertical pressure and temperature profiles, which are obtained in the OHP by radiosondes from Nîmes and, (b) the number of chosen layers which depend on the considered molecule, (tropospheric or stratospheric) and of the instrument spectral resolution.

It is clear that this retrieved profile is used again for a best determination of the total column content. As an example we recently published the vertical profile of N_2O derived from observations made with the SISAM above the OHP. To illustrate the method, Figure 13 shows the 3 different line shapes obtained using the three different supposed profiles shown in Fig. 13. In each case the total column content is the same.

In Figure 14, we give the example of fit between observed and calculated spectra leading to the vertical concentration profile given on Figure 15. The error bars in different layers are shown: the results obtained by in situ methods are also plotted.

In the case of N_2O (or H_2CO), which are mainly tropospheric, the SISAM spectral resolution (0.02 cm^{-1}) limits the retrieved profile height to an altitude of 30 kilometres.

For ozone, or other stratospheric molecules, this principle may be applied to spectrometer systems of higher resolving power e.g., Fourier Transform, or heterodyne laser. These are now working in Reims, and may be used to give very precise values of the molecular parameters needed for the analysis.

FIGURE 1.

Vertical Profile of Ozone
From the OHP, 3rd September 1983 a.m.

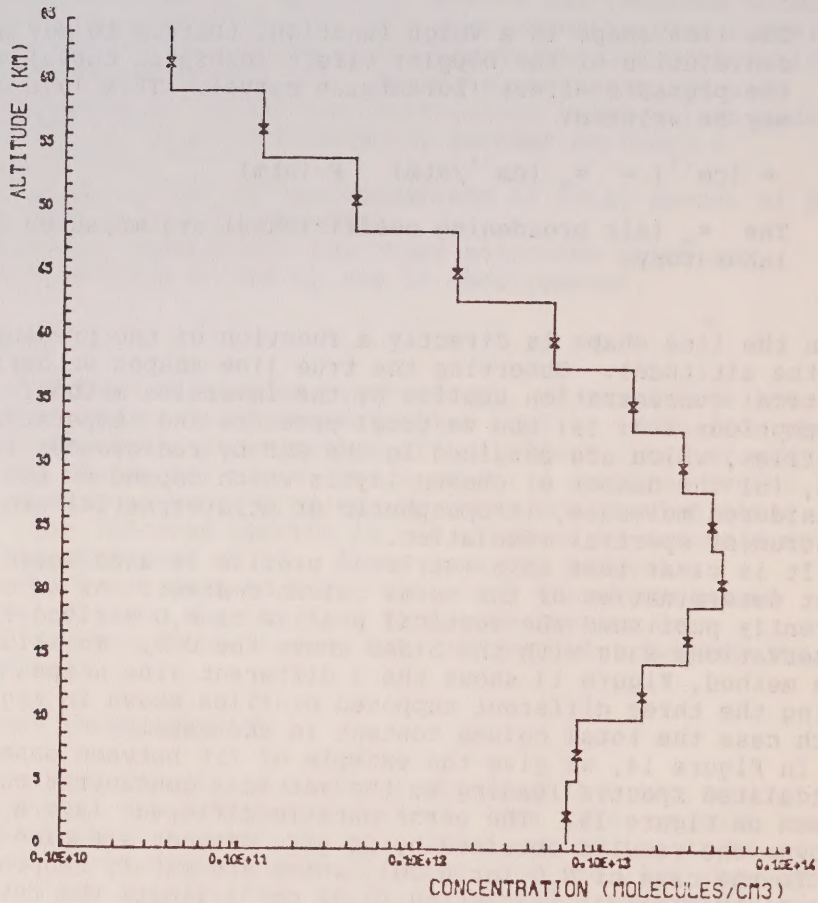
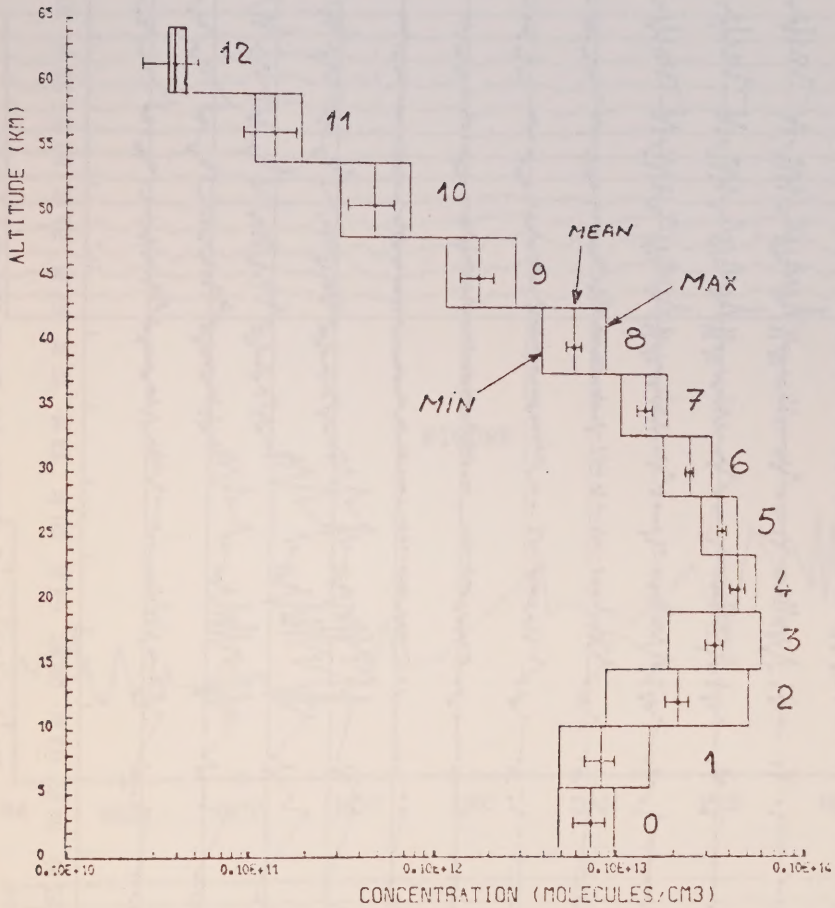
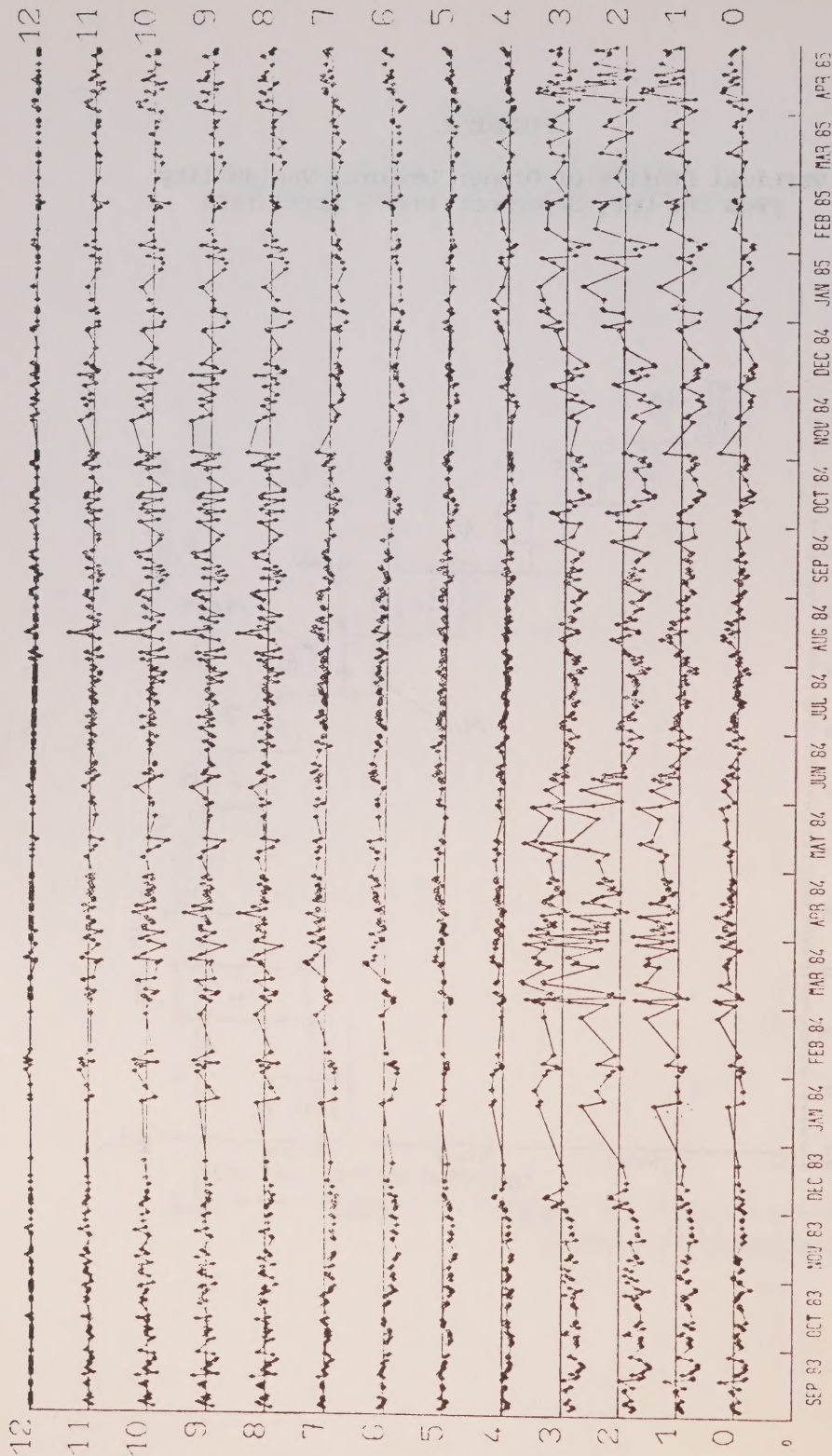


FIGURE 2.

Vertical Profile of Ozone: Temporal Variability
From the OHP, September 1983 - April 1985





Variability of Ozone in Each Umkehr Layer
Haute Provence Observatory
Instrument #85

FIGURE 3.

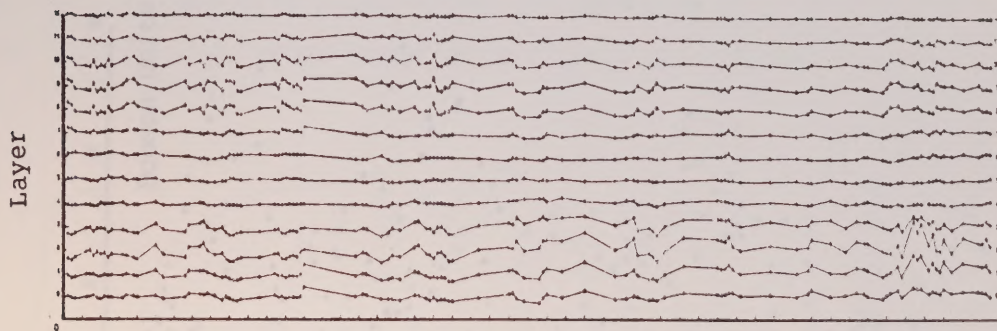
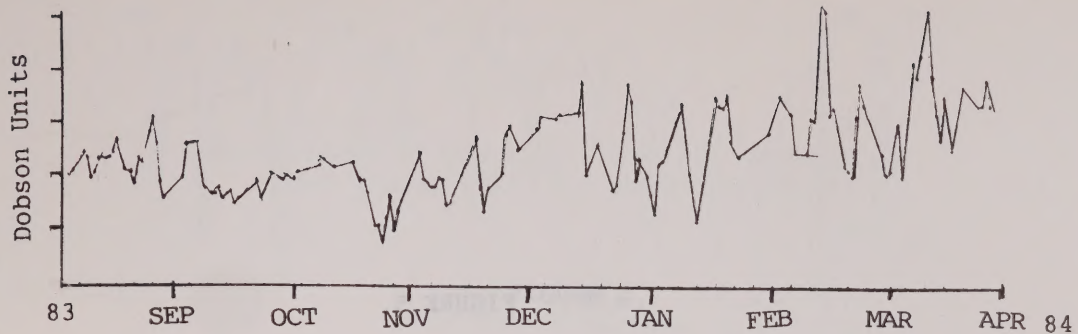


FIGURE 4.

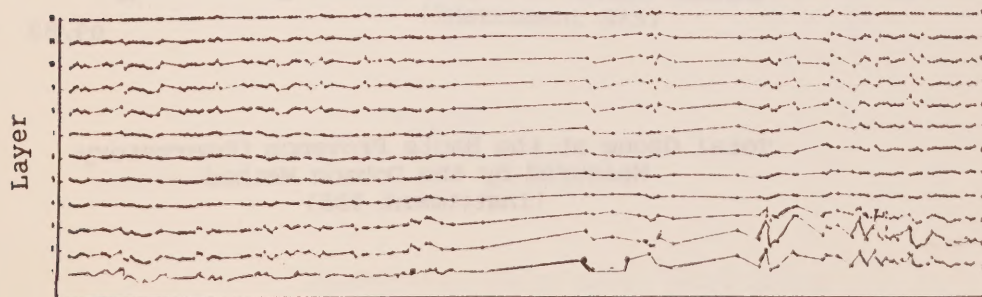
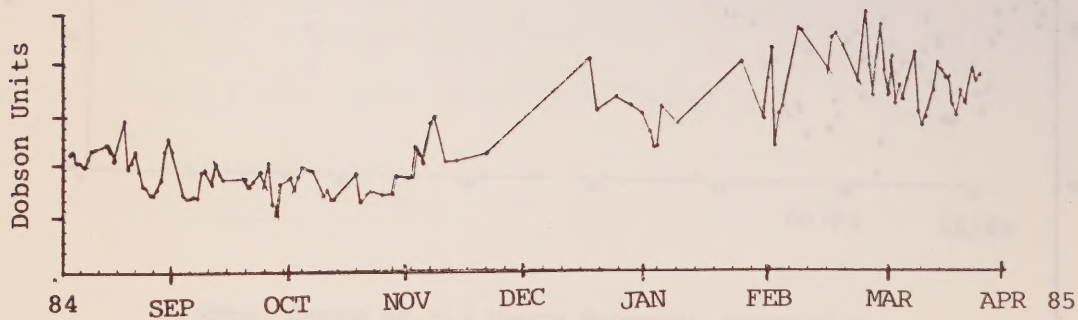
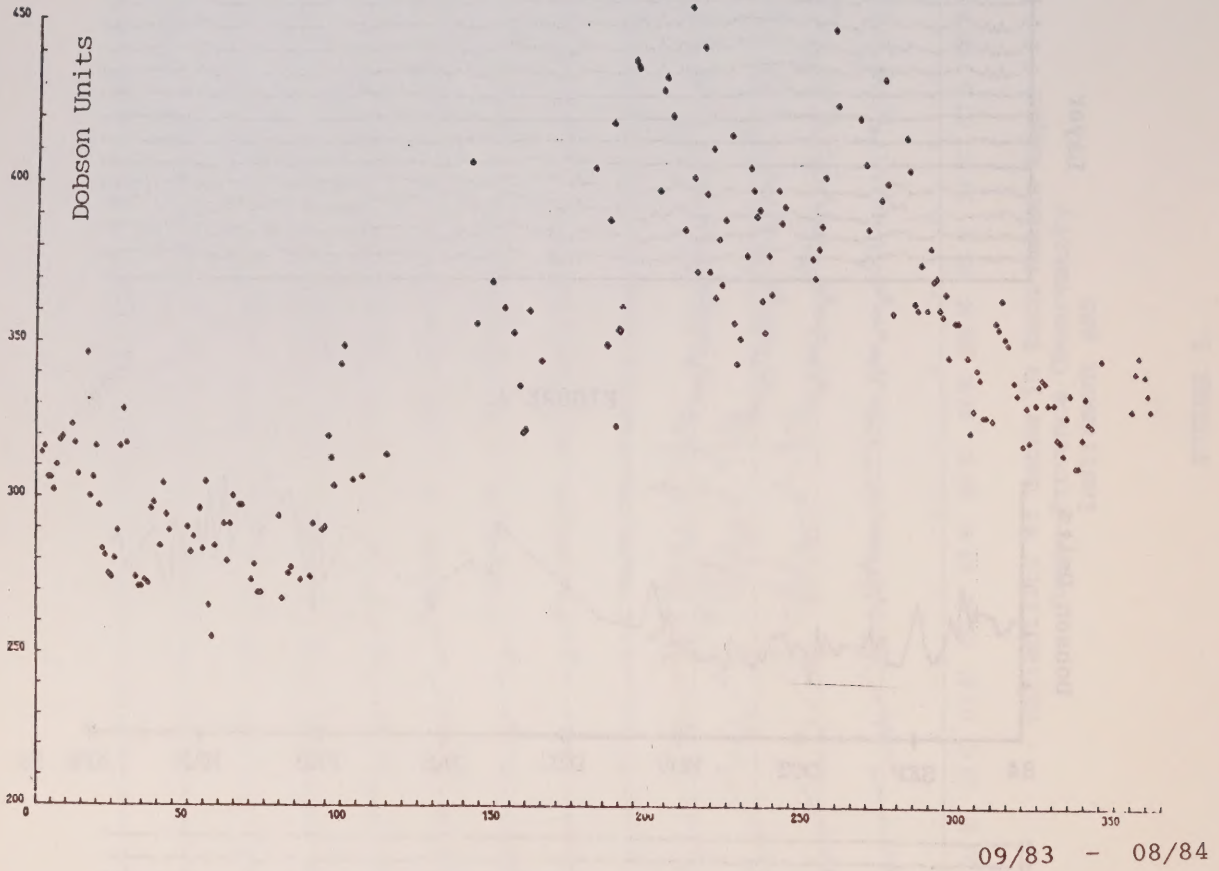
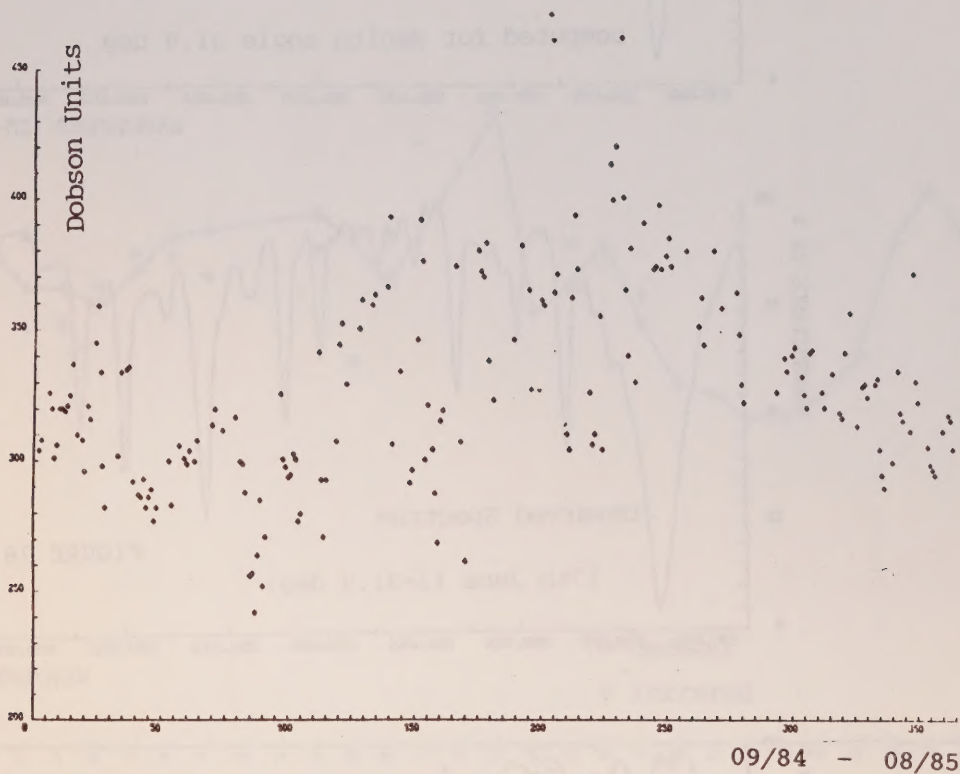


FIGURE 5.



Total Ozone at the Haute Provence Observatory
Measured by the Dobson Method
(Instrument #85)

FIGURE 6.



Total Ozone at the Haute Provence Observatory
Measured by the Dobson Method
(Instrument #85)

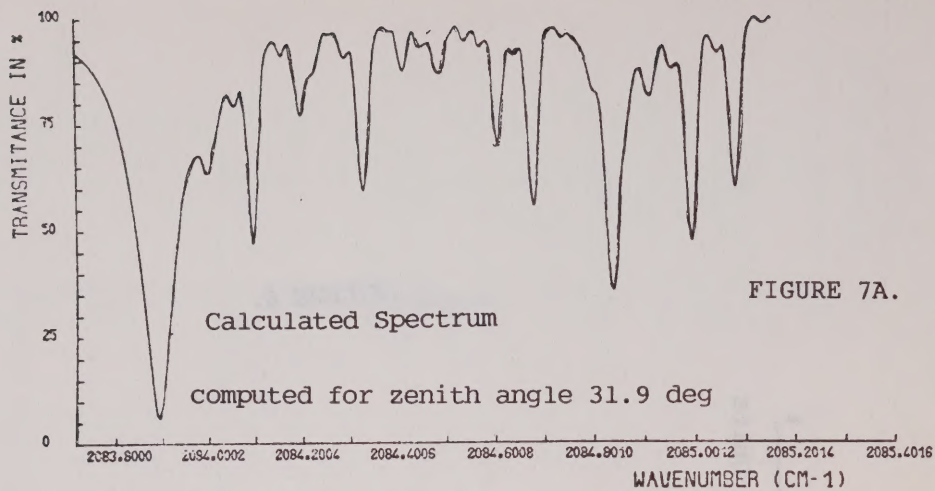


FIGURE 7A.

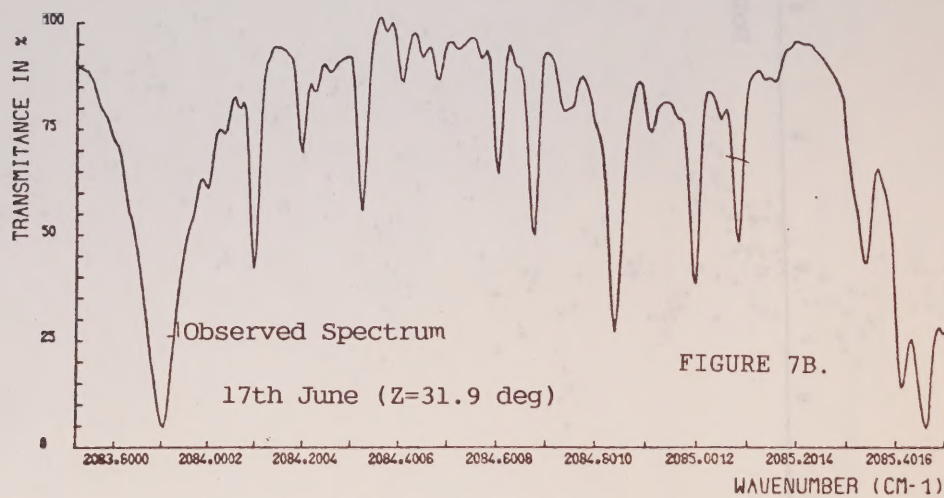


FIGURE 7B.

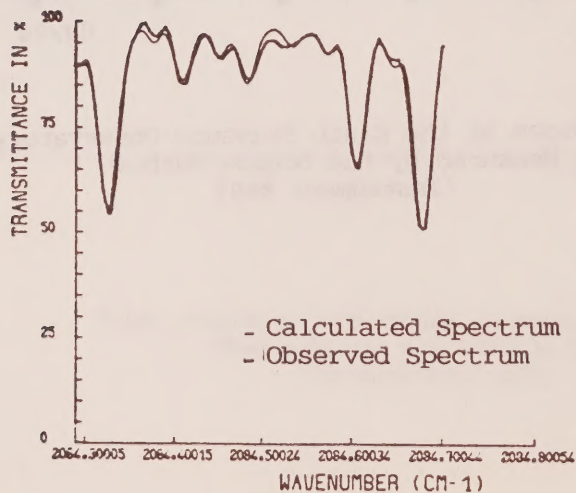


FIGURE 7C.

Total Ozone at the Haute Provence Observatory
Mont Chiran (IR), St. Michel (Dobson)

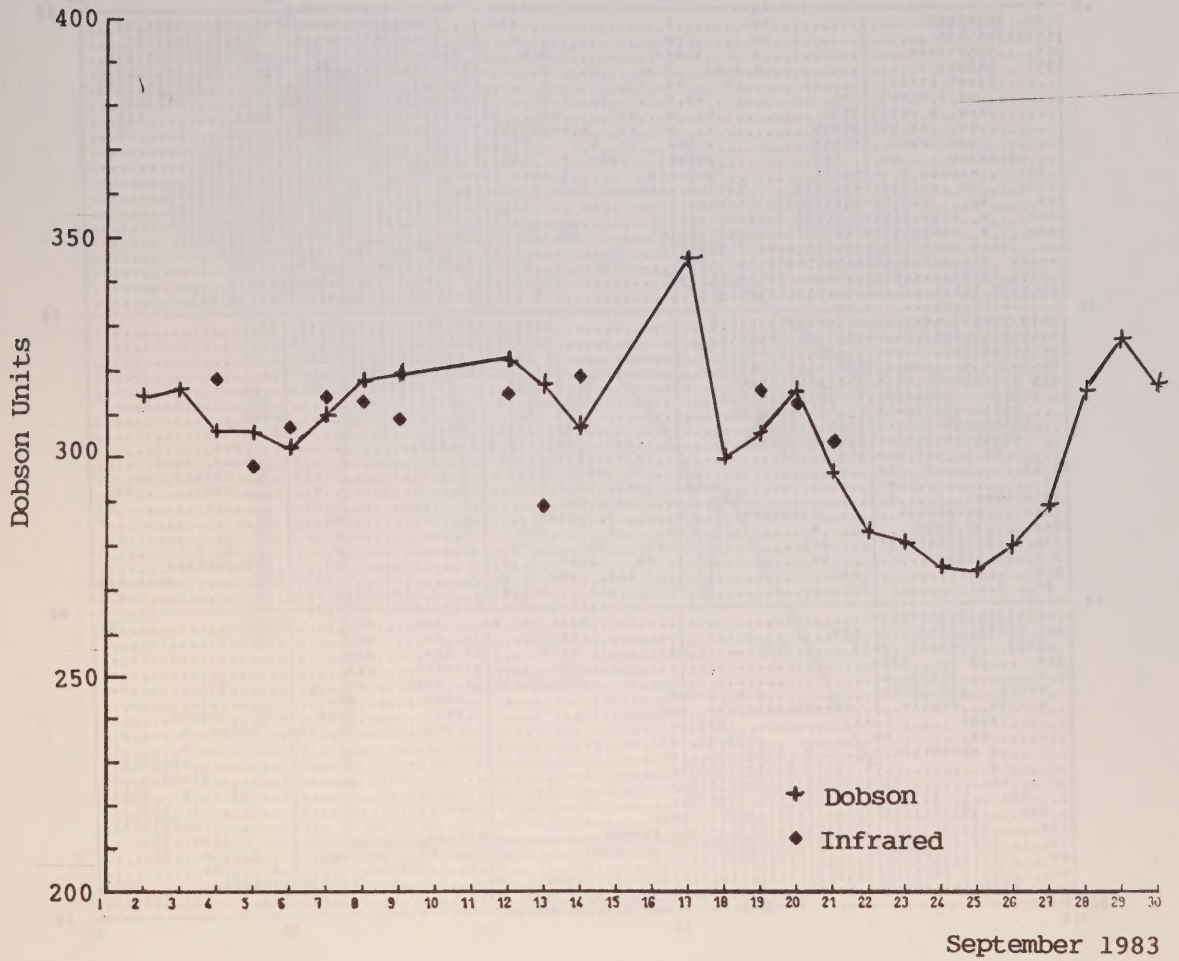
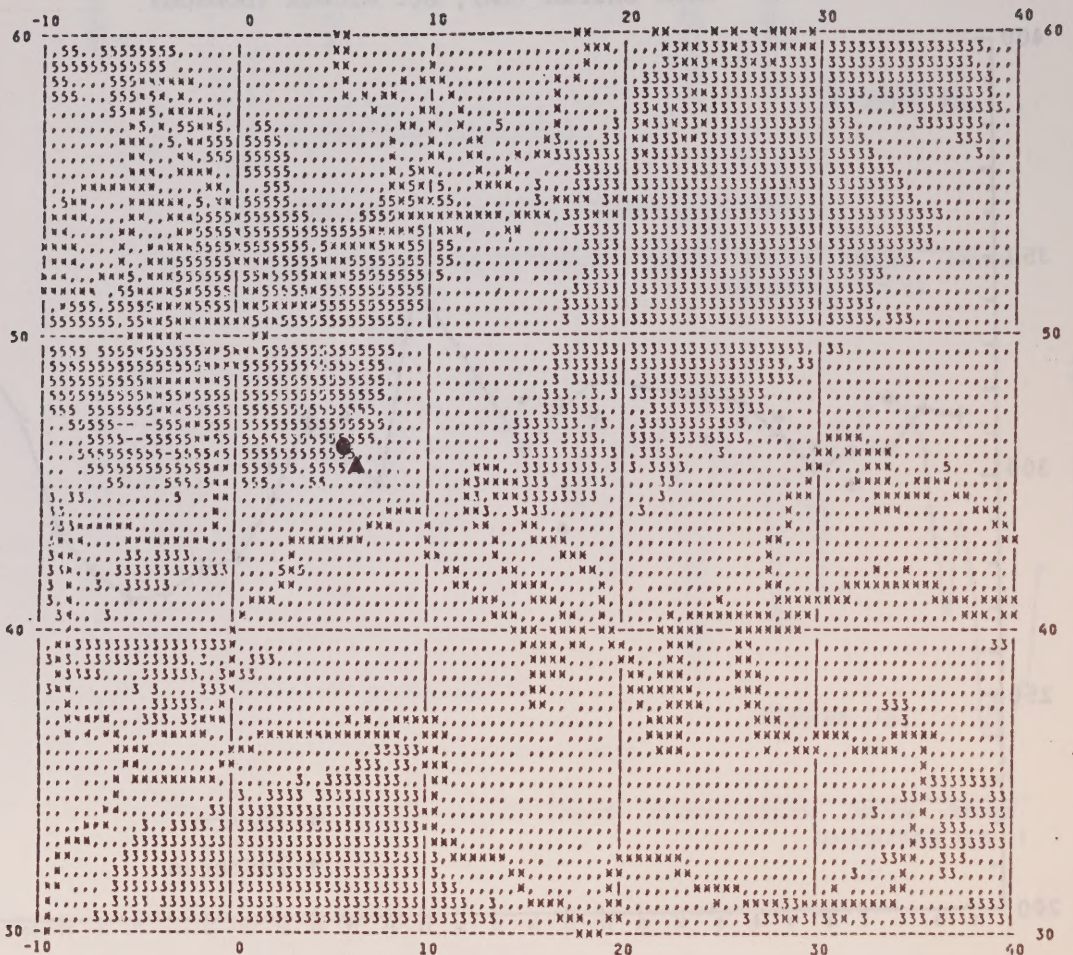


FIGURE 8.

TOMS



● OHP St Michel OHP Mt Chiran ▲

FIGURE 9.

FIGURE 10.

Observations At The Haute-Provence
Observatory

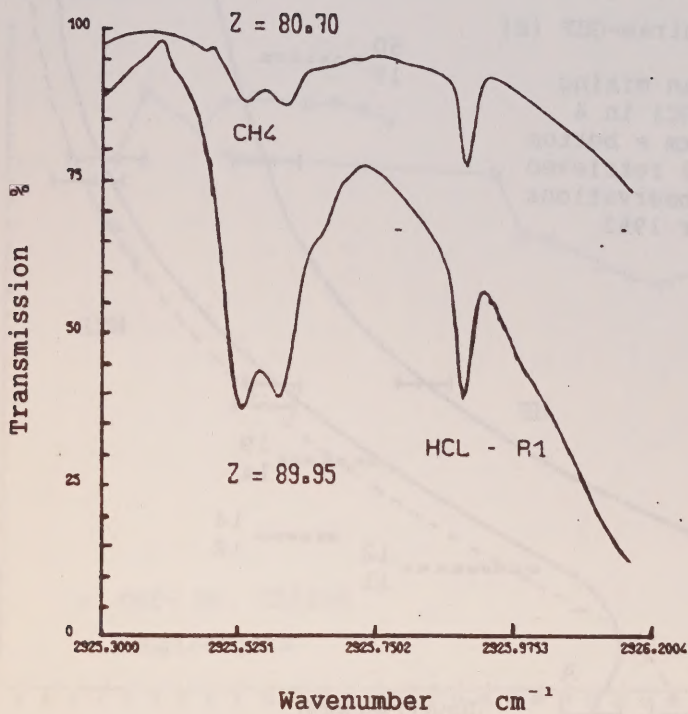


FIGURE 11.

Typical Profiles Fitting MAP-GLOBUS Observations

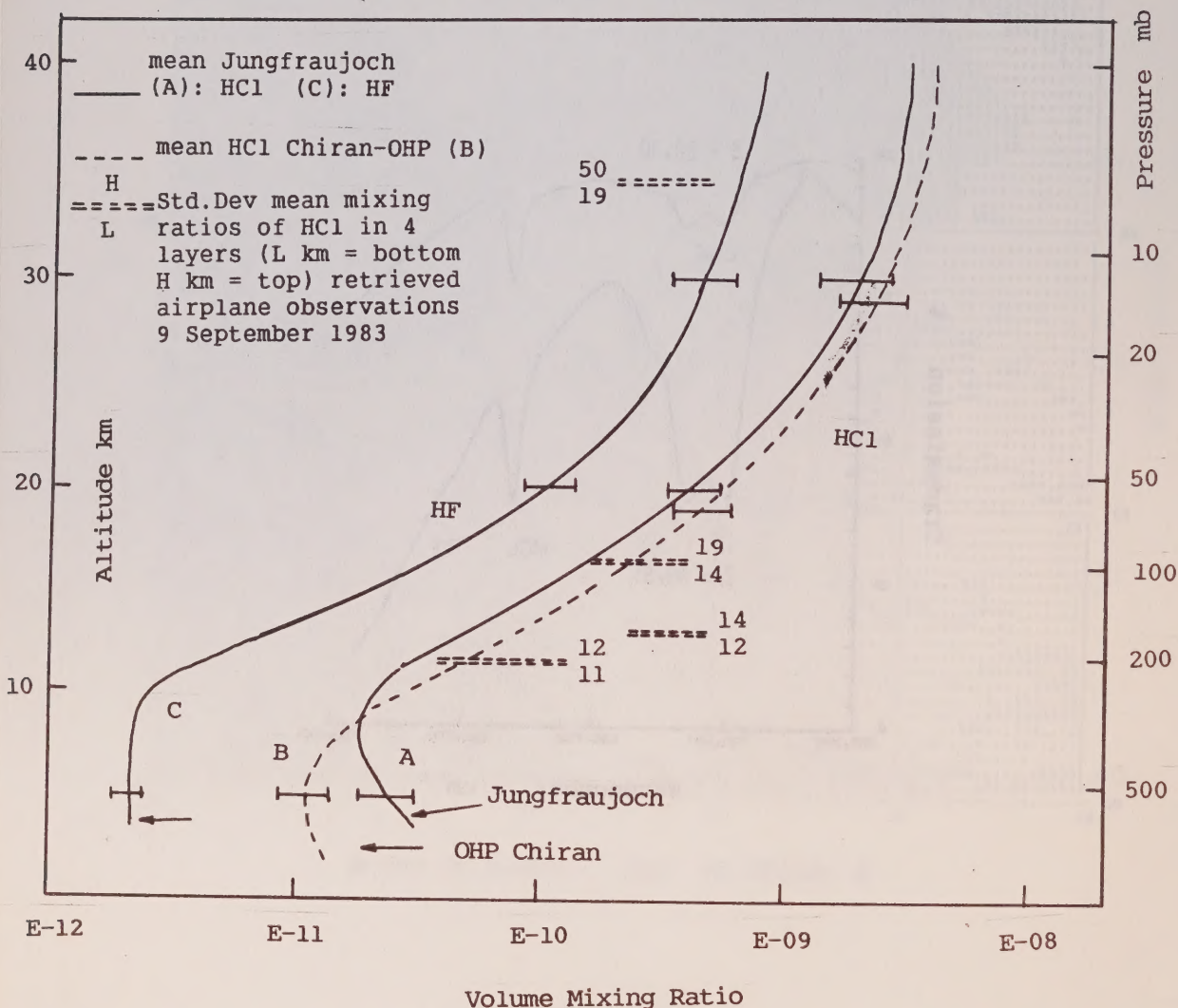
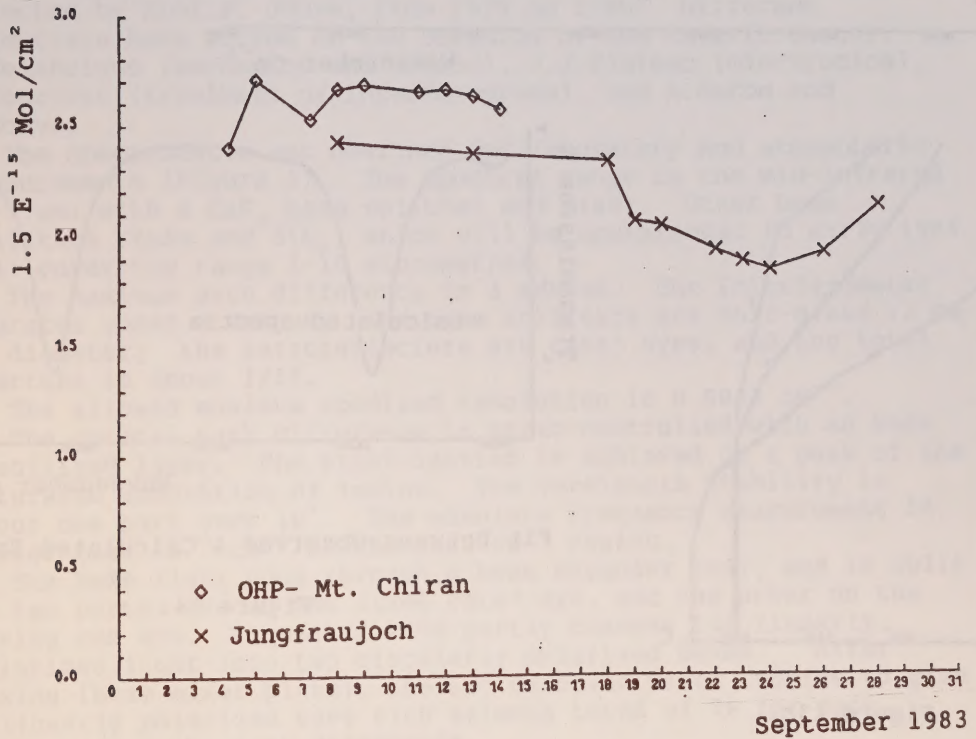
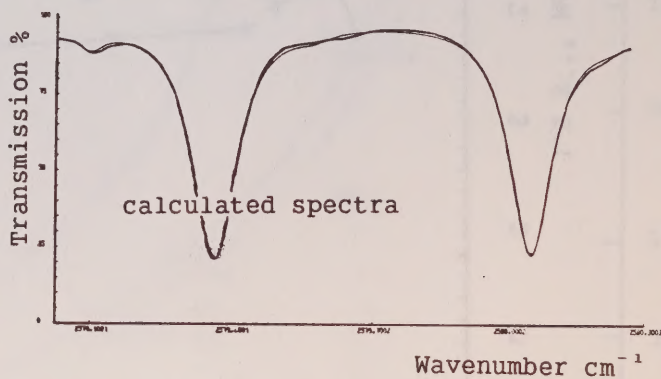
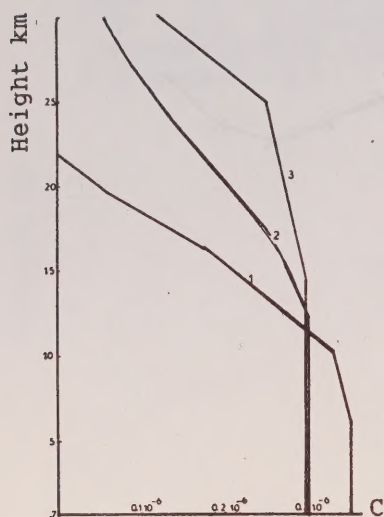
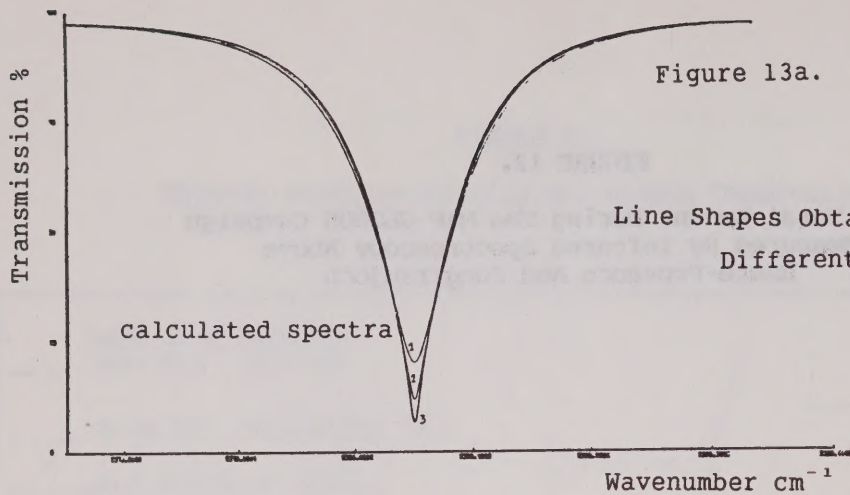


FIGURE 12.

HCl: Total Amount During The MAP-GLOBUS Campaign
Measured By Infrared Spectroscopy Above
Haute-Provence And Jungfraujoch





Fit Between Observed & Calculated Spectra

Figure 14.

Figure 13b.

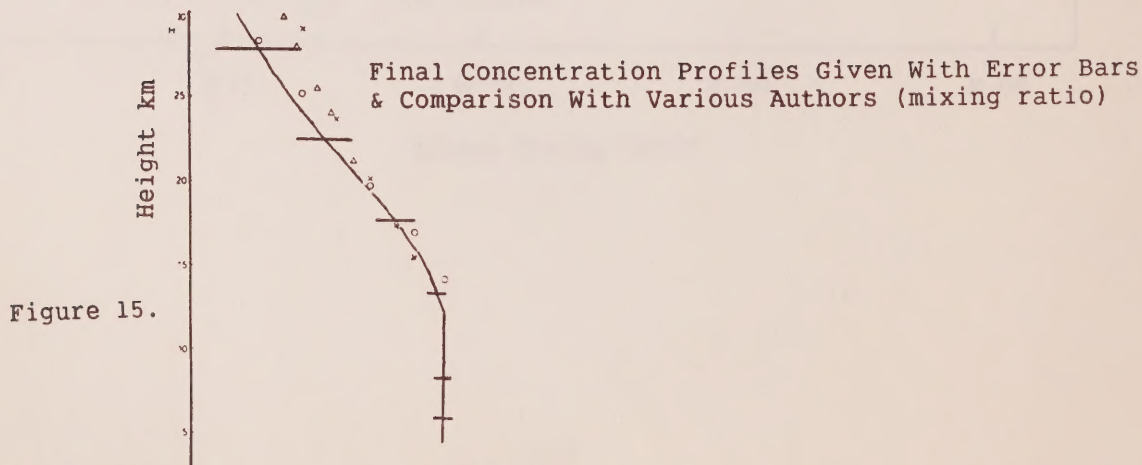


Figure 15.

A Fourier Transform Spectrometer

Pierre Marché

Université de Reims

This spectrometer was built in the Laboratory of Atmospheric and Molecular Spectroscopy, Reims, France (UA CNRS 776) which was directed by Prof. P. Jouve, from 1979 to 1985. Different scientists have worked on the building of the interferometer: A. Delahaigue (mechanics and optics), J. J. Plateau (electronics), D. Courtois (treatment of interferograms), and A. Barbe and P. Jouve.

The spectrometer was designed for laboratory and atmospheric measurements (Figure 1). The spectral range is the mid-infrared (2-7 μm) with a CaF_2 beam splitter and mixer. Other beam splitters (ZnSe and SiO_2) which will be operational in early 1986 will cover the range 1-15 micrometres.

The maximum path difference is 3 metres. The interferometer operates under a vacuum. The beam splitters are half-disks 12 cm in diameter; the retroreflectors are cats' eyes, and the total aperture is about $f/10$.

The allowed maximum apodized resolution is 0.0033 cm^{-1} .

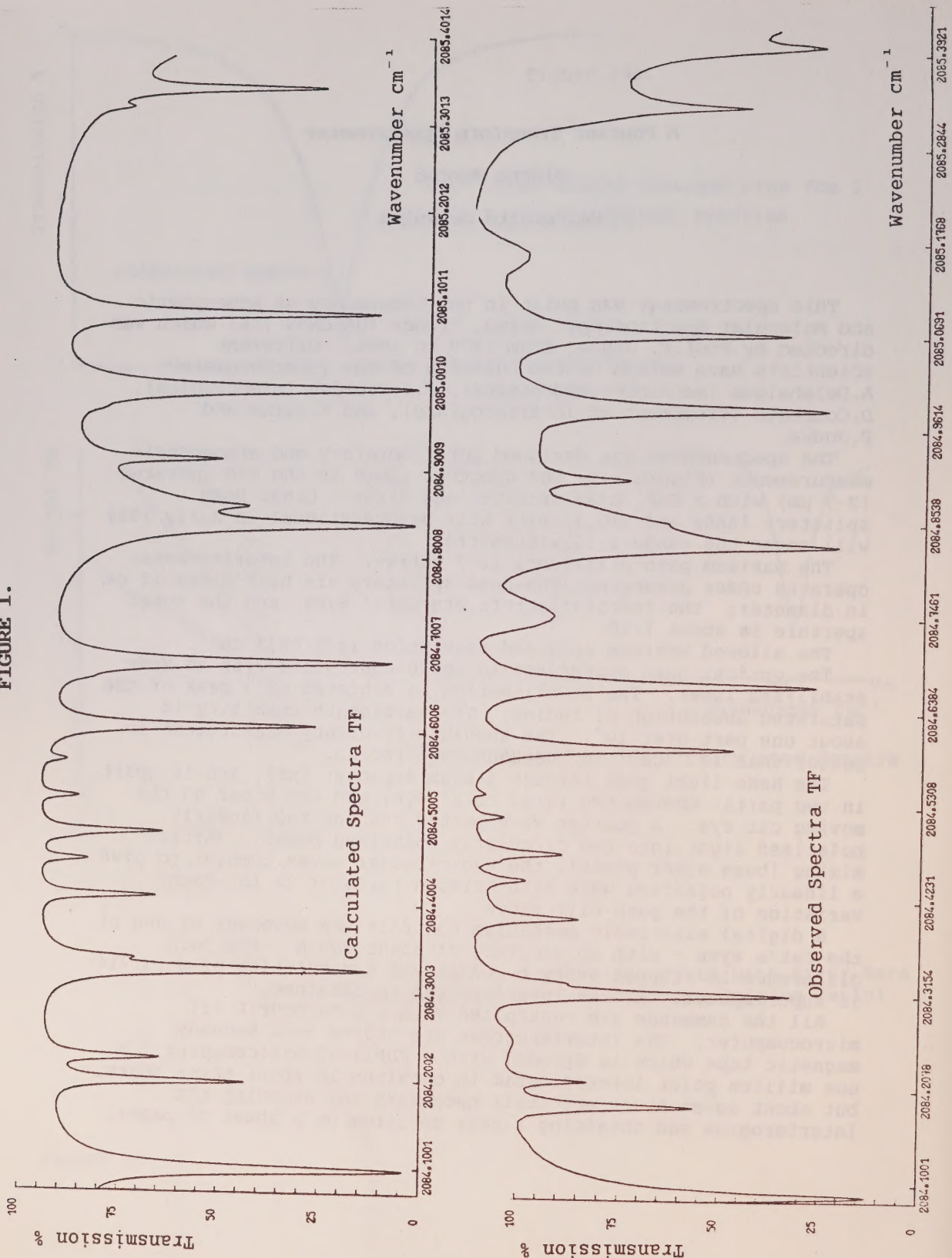
The optical path difference is servo-controlled with an HeNe stabilized laser. The stabilization is achieved on a peak of the saturated absorption of iodine. The wavelength stability is about one part over 10^9 . The absolute frequency measurement is better than 10^{-5} cm^{-1} in the 2000 cm^{-1} region.

The HeNe light goes through a beam expander (x5), and is split in two parts: one on the fixed cats' eye, and the other on the moving cat eye. A quarter wave partly changes the linearly polarized light into two circularly polarized beams. After mixing (beam mixer plate), the two circular waves combine to give a linearly polarized wave with azimuth turns of 2π for each variation of the path difference.

A digital electronic mechanism controls the movement of one of the cat's eyes - with an accuracy of about 500 Å - the path difference is stepped every $p \cdot \lambda/16$ and a modulation of $q \cdot \lambda/16$ is superimposed. A sine interferogram is obtained.

All the commands are controlled with a Z-80 GOUPIIL III microcomputer. The interferograms are stored on a Kennedy magnetic tape which is decoded with a PDP11.33 minicomputer. A one million point interferogram is obtained in about three hours, but about seven hours are still necessary for decoding the interferogram and obtaining a real spectrum on a sheet of paper.

FIGURE 1.



Comparisons of Observed and Calculated Spectra

David G. Murcray

Department of Physics
University of Denver

Our group at the University of Denver has been obtaining infrared solar and atmospheric emission spectra from the ground, aircraft and balloons for many years. Rather than discussing the instrumentation used and the results obtained during these studies, I want to emphasize the analysis that has been performed on selected samples of the data. Early detection of changes in the earth's optical characteristics which will result in climatic change will depend on accurately predicting the flow of radiation in the earth's atmosphere. In fact, if this can be done with sufficient accuracy the problem of how to detect changes in the climate caused by increasing emissions of the radiatively active compounds can be done by directly measuring the concentration of these compounds. The question of the accuracy which we can currently achieve in radiative transfer calculations is the one I will emphasize in this presentation.

The results I will present were obtained as part of a study of the inverse problem, i.e., given a high-resolution infrared solar spectrum, what information can be retrieved concerning the altitude distribution of the constituent responsible for the absorption feature. For this analysis we use the non-linear least squares technique developed by Nijil and Goldman. This technique uses line-by-line calculations and fits a number of parameters using all of the spectral detail present. The experimental spectra used in this analysis were obtained at the South Pole. This site turns out to be one of the best sites in the world for ground-based studies due to its high altitude and cold temperatures. Figure 1. shows the agreement in the $947\text{--}949\text{ cm}^{-1}$ region between calculated and observed spectra. The calculated spectrum is the solid line, the experimental is the dashed. The spectral data were calculated using a fixed uniform mixing ratio for the CO_2 , the atmospheric profile observed by a sonde run on the day of the observation. The H_2O profile used in the fitting was chosen to fall off with altitude. The amounts of water vapour and carbon dioxide, determined by fitting the spectra in this and other regions, was 0.8 ppm of H_2O , and a uniform mixing ratio of 310 ppm for carbon dioxide. The residual errors in the least squares determination yield an estimated absolute accuracy of fifteen percent. Ground based CO_2 measurements at South Pole were in the range of 330 parts per million.

Figure 2. shows an attempt to fit the 1248 cm^{-1} region using a uniformly merged N_2O profile. Figure 3. shows a similar fit where a more realistic N_2O profile is used, ie. uniform merging in the troposphere with a rapid fall off above the tropopause. The tropospheric merging ratio in this case determined by the fit is 3.0 parts per billion. Figure 4. shows the fit in the 1247 to 1249 cm^{-1} region which contains a strong feature due to methane. In this case, the absorption can be fit using a uniformly merged CH_4 profile or a more realistic profile with a rapid decrease in CH_4 above the tropopause. The profile which decreases with altitude yields a 1.6 ppm tropospheric concentration of methane.

The early spectra were chosen because they represent absorption features due to compounds which are felt to be in "good" shape spectroscopically. At the other extreme I offer the current status on line-by-line analysis of the 923 cm^{-1} absorption CF_2Cl_2 . Figure 5. shows the comparison between laboratory CF_2Cl_2 absorption and those due to theoretical calculations using line parameters determined for this band. While the agreement is far from good, it is certainly not bad when one considers that this is the first attempt to calculate this transmission on a line-by-line basis. The complexity of the region is shown in Figure 6. which lists some of the vibrational bands involved in the absorption. Figures 7-9. show this spectral region as observed in solar spectra taken over the last 10 years. The first of these show spectra obtained from Denver in 1976, the second from the South Pole in 1980, and finally from Lander, New Zealand in 1985. Figure 10. shows the growth of this spectral region during sunset from balloon altitudes.

A final example of a data set which can be used to test our analytic capability is shown in Figure 11. This is a small portion of a spectrum obtained with a liquid nitrogen cooled interferometer system. The spectrum was obtained from a balloon at $75,000$ feet while viewing the radar. The spectrum is calibrated absolutely, the spectral resolution is 0.06 cm^{-1} . This spectral region is used by most meteorological satellites as one of the channels which gives information concerning the atmospheric temperature at mid-to-high tropospheric altitudes. It is in this spectral region that the major change in atmospheric emission due to an increase in atmospheric CO_2 will occur.

FIGURE 1.

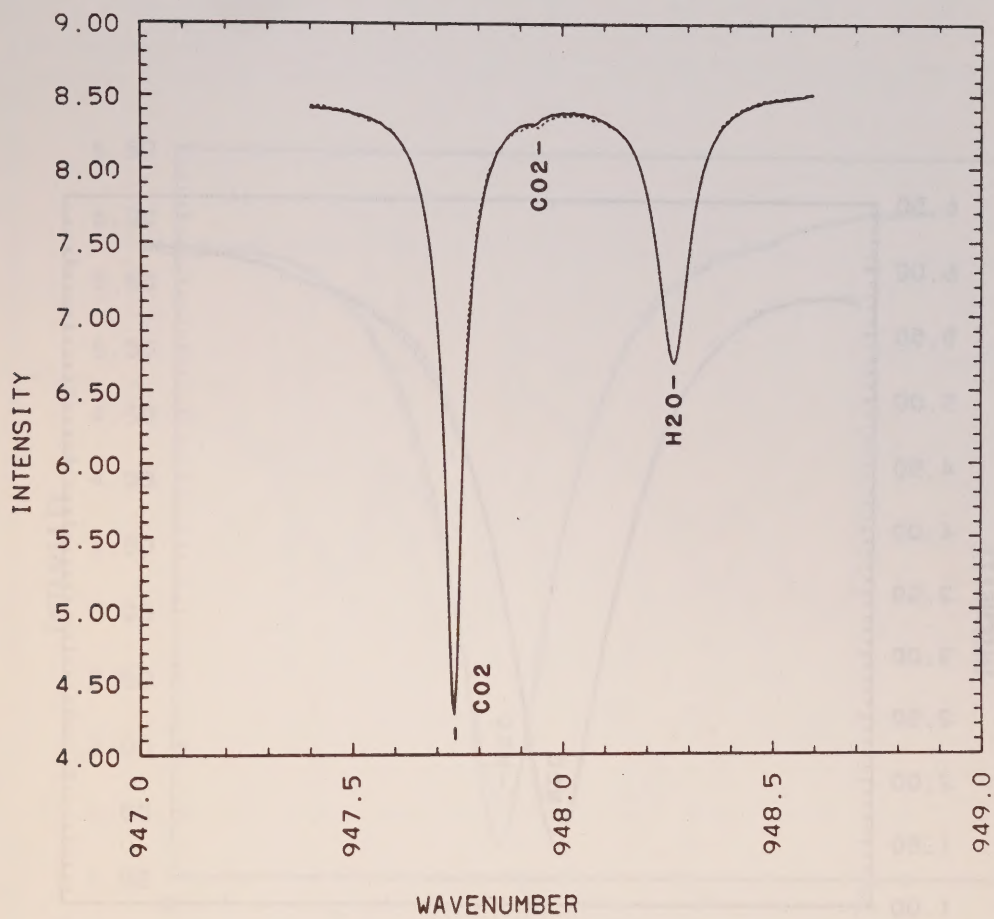


FIGURE 2

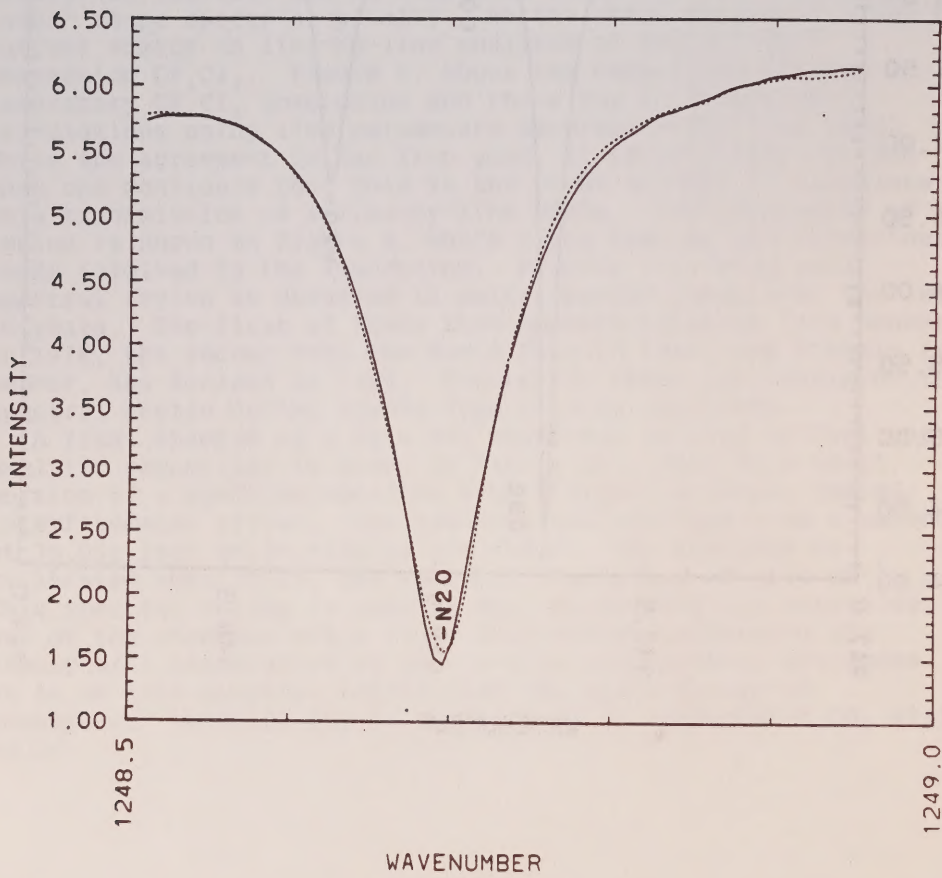


FIGURE 3.

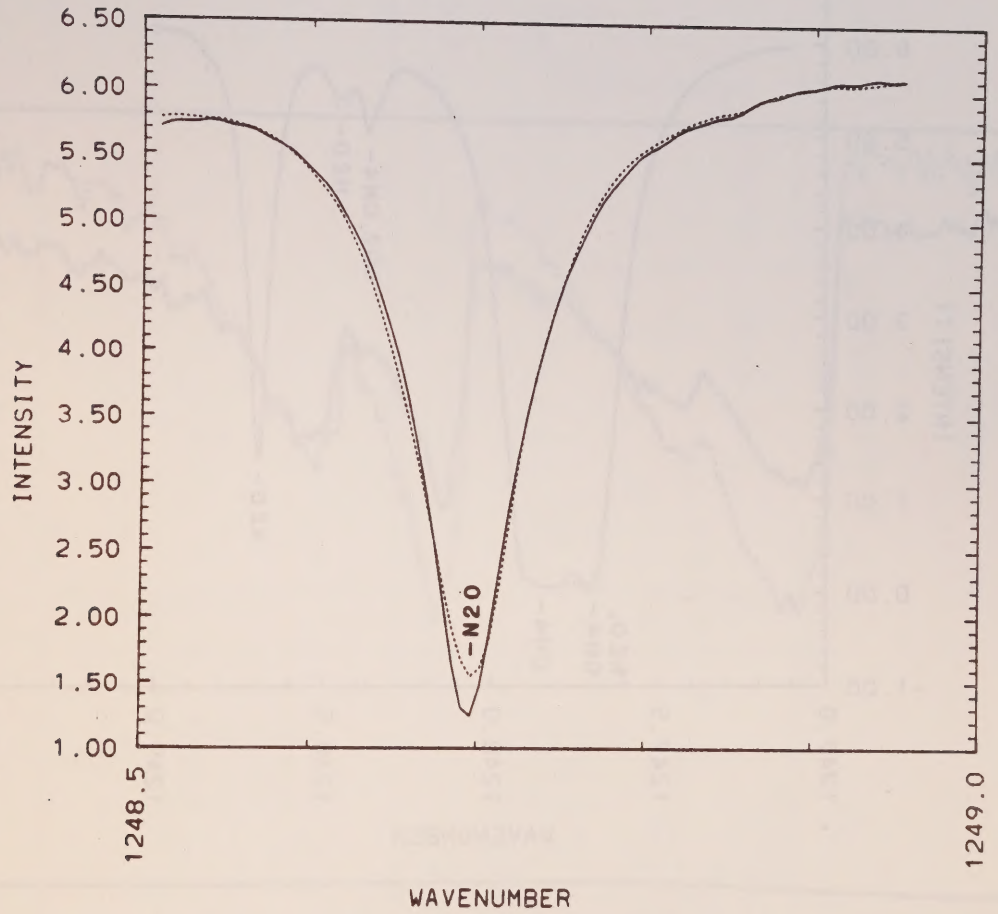


FIGURE 4.

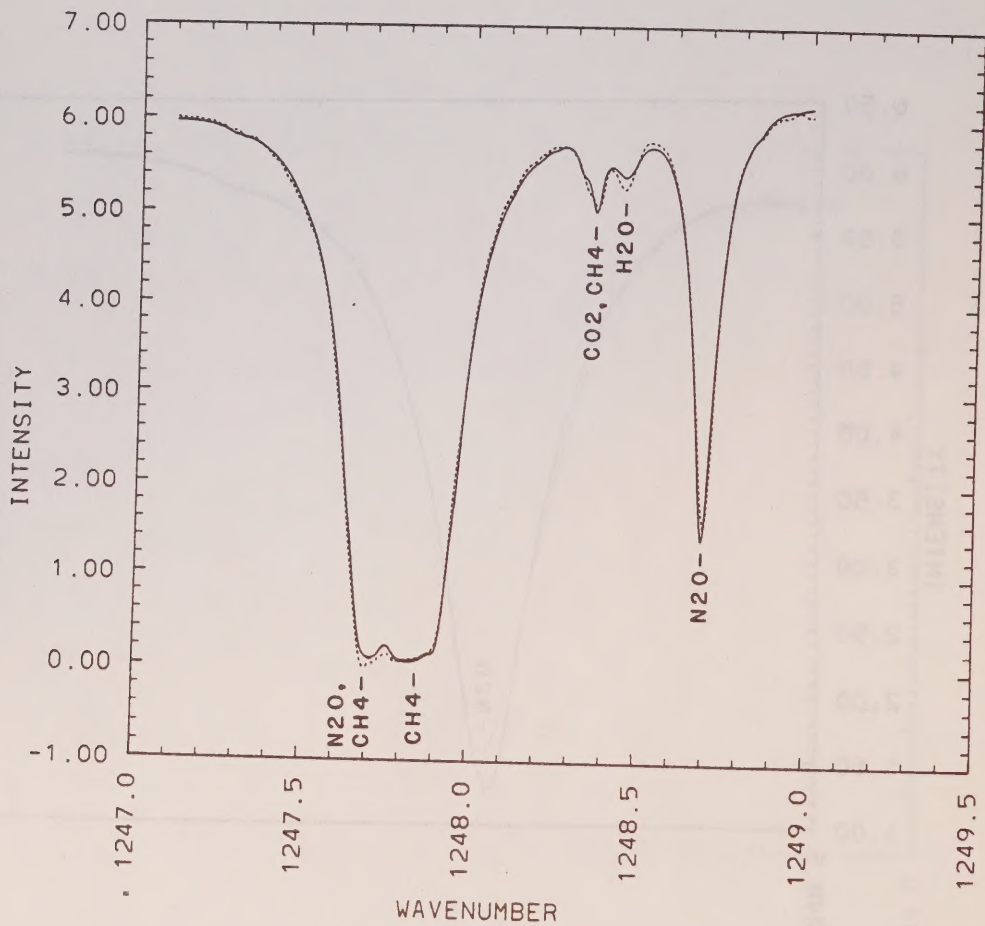
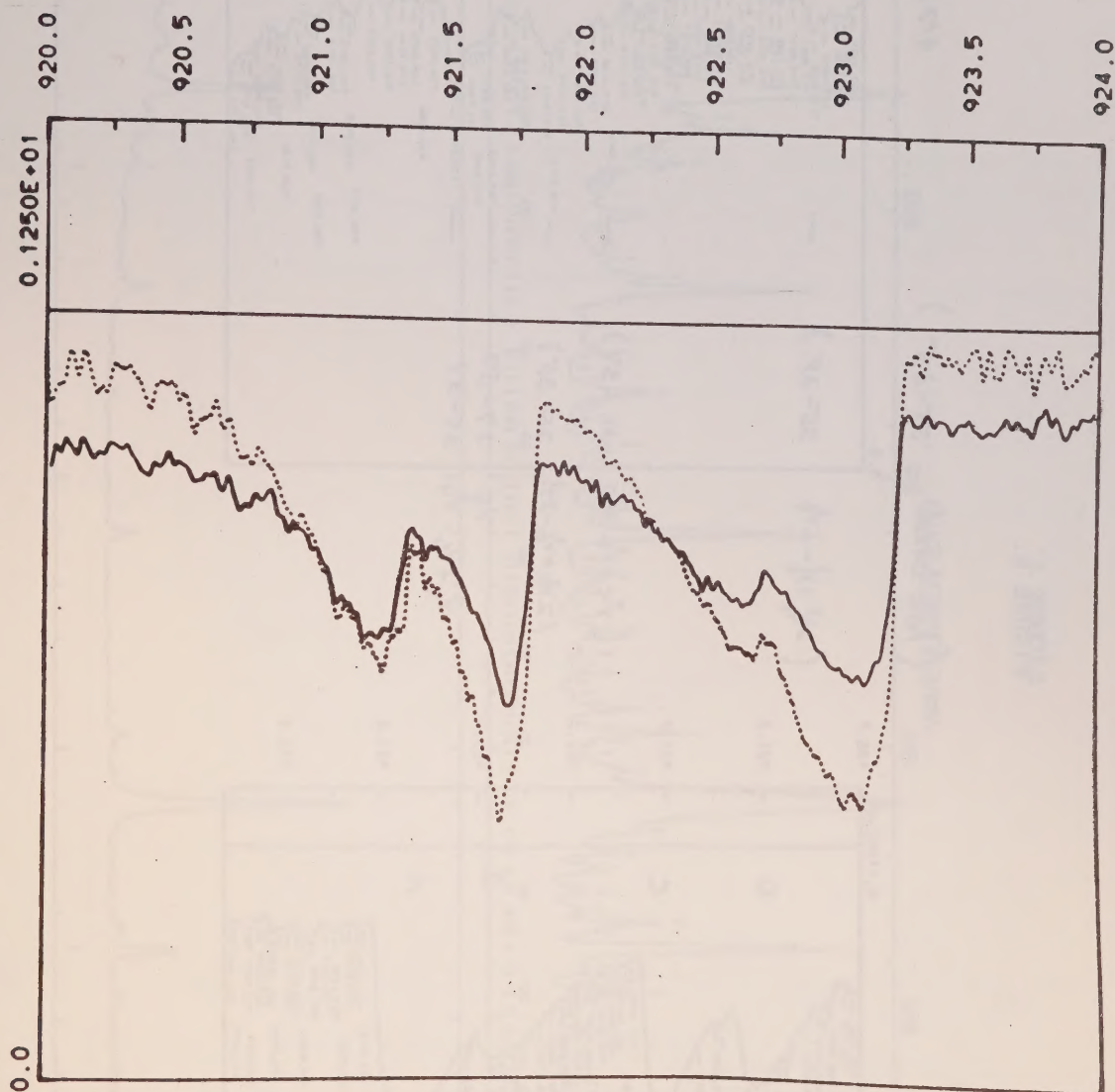


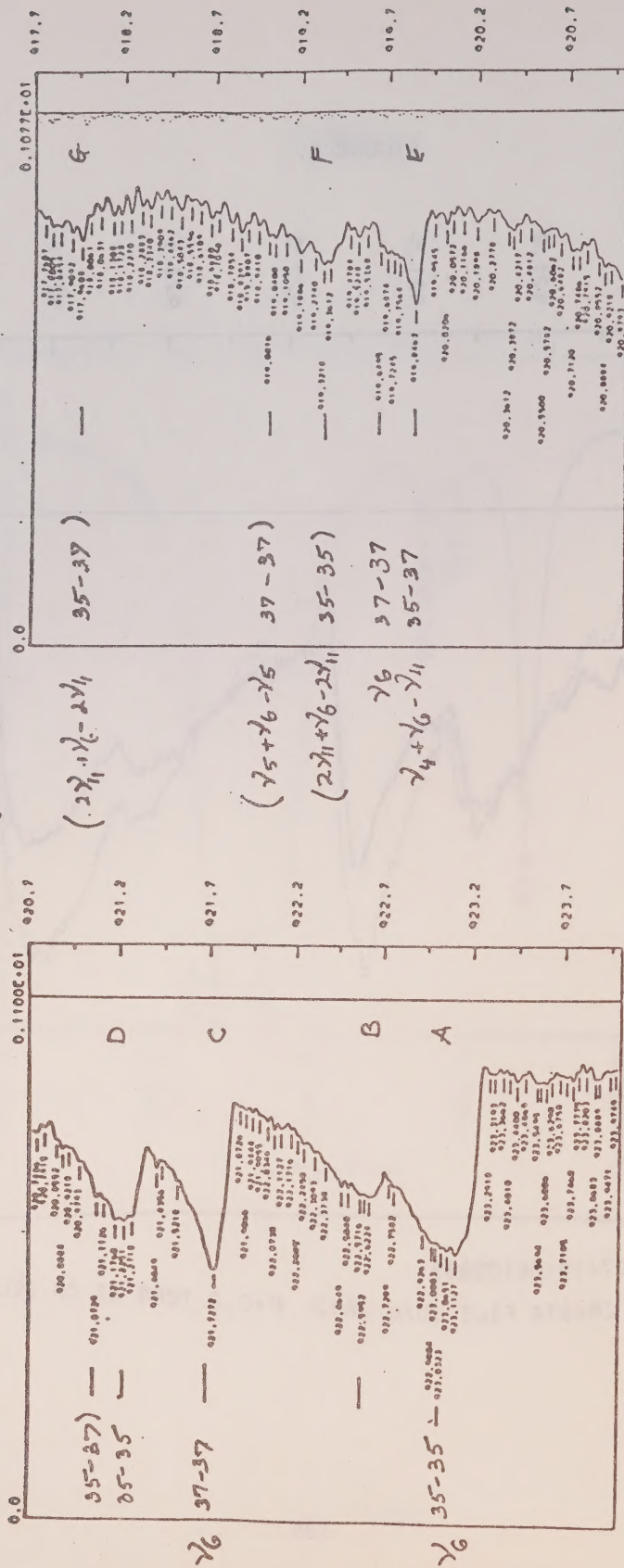
FIGURE 5.



07/18/86105885

CHAST4 FILS 10/6 FR12 P=0.2 TORR 22 CM CELL

(hot band 35-35)



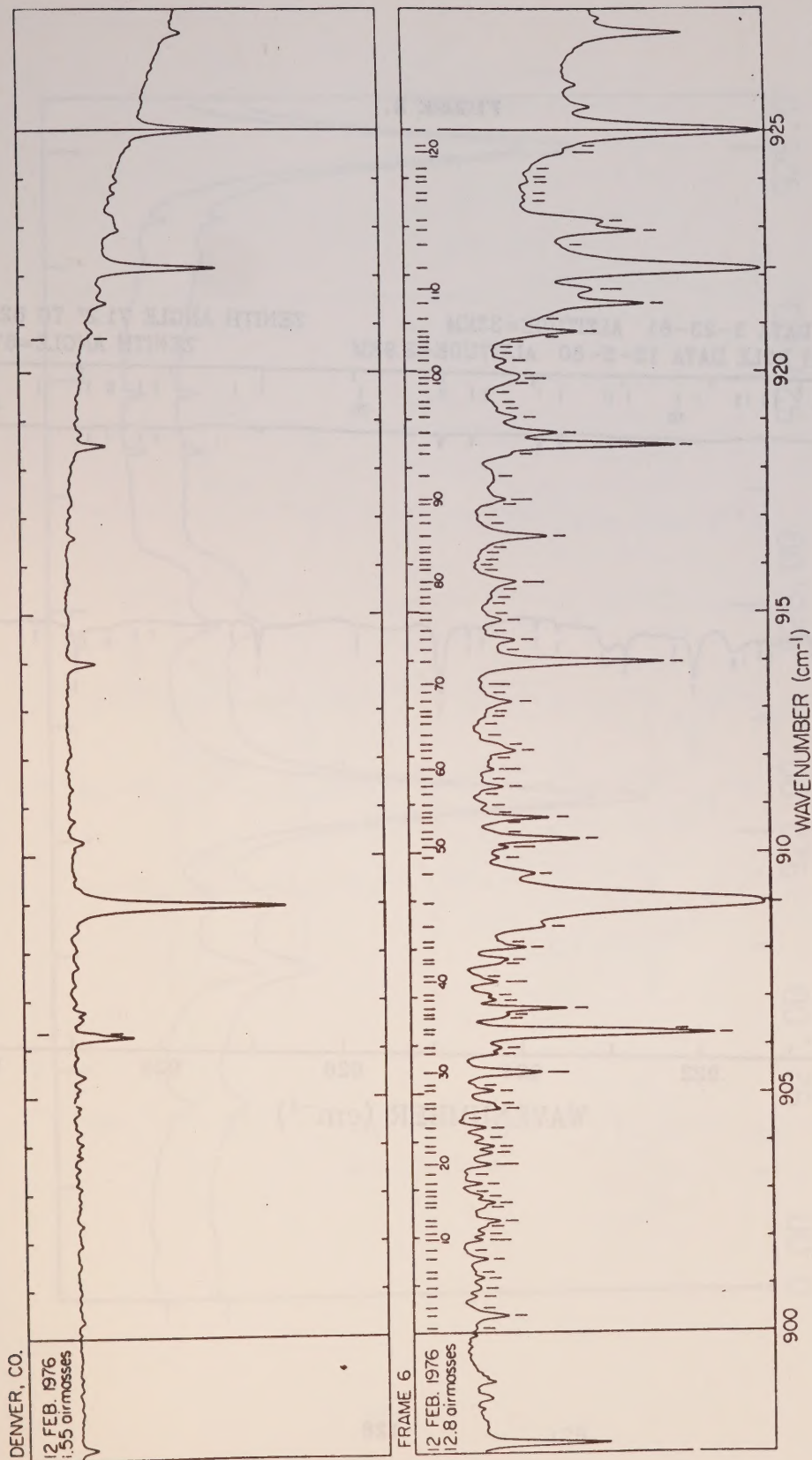
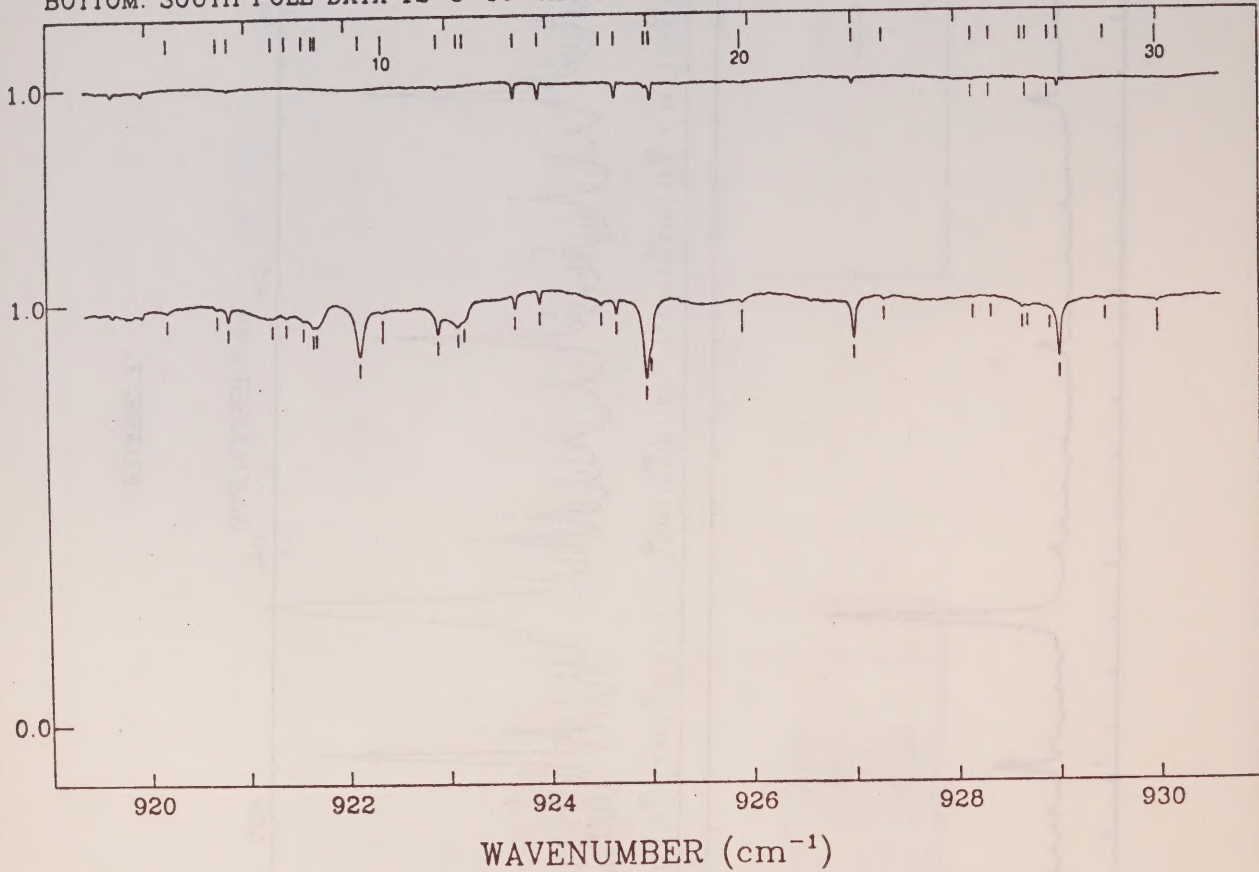


FIGURE 7.

FIGURE 8.

TOP: BALLOON DATA 3-23-81 ALTITUDE=33KM
BOTTOM: SOUTH POLE DATA 12-5-80 ALTITUDE=2.9KM

ZENITH ANGLE 71.2° TO 82.0°
ZENITH ANGLE=67.7°



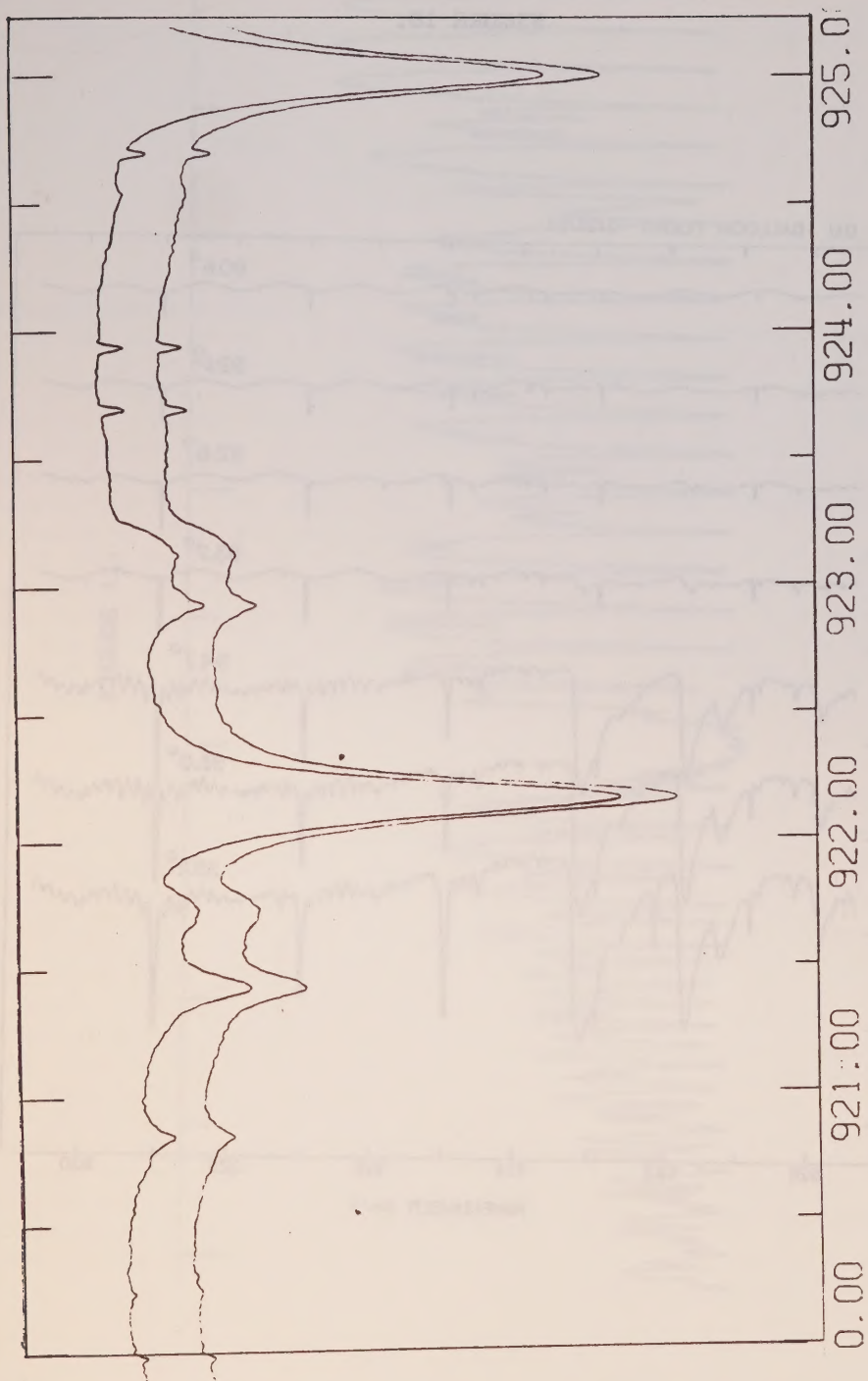


FIGURE 9.

FIGURE 10.

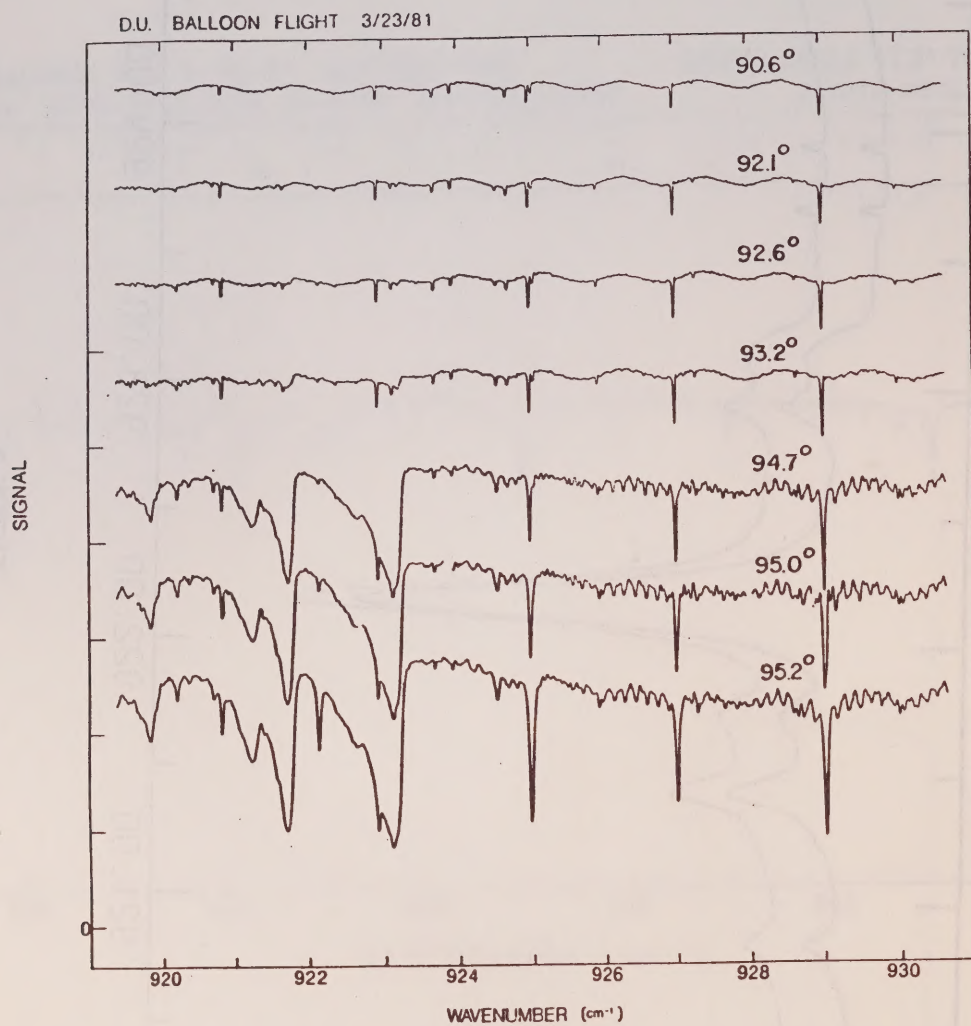
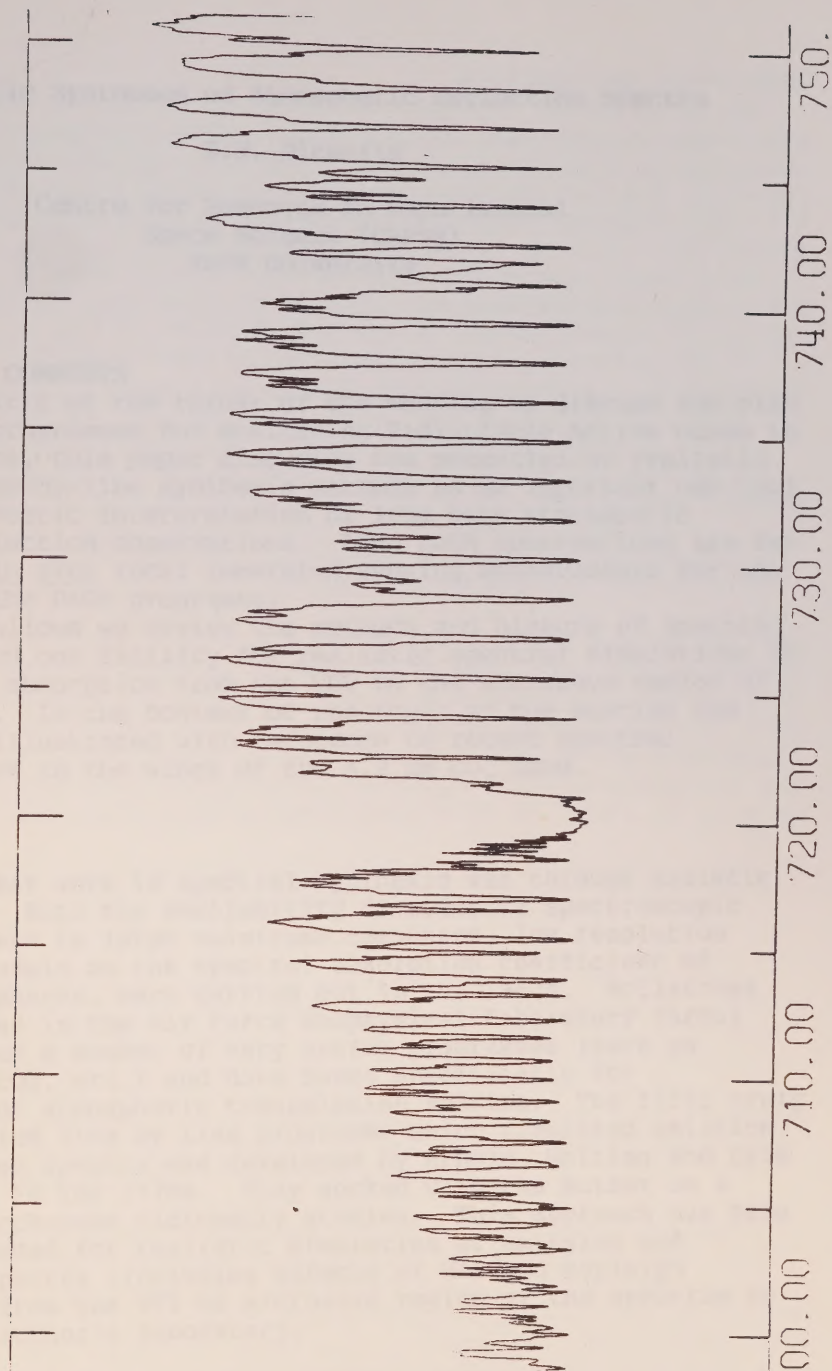


FIGURE 11.





Realistic Syntheses of Atmospheric Extinction Spectra

R.W. Nicholls

Centre for Research in Experimental
Space Science (CRESS)
York University

INTRODUCTORY COMMENTS

In the spirit of the thrust of the meeting to discuss and plan methods and programmes for monitoring Radiatively Active Gases in the atmosphere, this paper discusses the potential of realistic numerical line-by-line synthesis methods as an important new tool for the diagnostic interpretation of long path atmospheric spectral extinction observations. Long path observations are far superior to in situ local immersion sensing measurements for the purposes of the RAGS programme.

In what follows we review the methods and history of spectral synthesis, and our facility for realistic spectral simulations in emission and absorption from the VUV to the microwave region of the spectrum. In the context of the topic of the meeting the methods are illustrated with reference to recent spectral synthesis work in the wings of the $4.3 \mu\text{m}$ CO_2 band.

HISTORY

The earliest work in spectral synthesis was through analytic band models. With the availability of moderate spectroscopic data and access to large mainframe computers, low resolution energy bin models on the spectral absorption coefficient of heated atmospheres, were carried out in the 1960s. McClatchey and colleagues in the Air Force Geophysical Laboratory (AFGL) have developed a number of very useful programmes (such as Lowtran, FASCOD, etc.) and data bases specifically for calculation of atmospheric transmission spectra. The first truly high resolution line by line programme which simulated emission and absorption spectra was developed by Arnold, Whiting and Lyle at NASA-Ames in the 1970s. They worked with the author on a number of shock-tube radiometry studies. This approach has been greatly extended for realistic simulation of emission and absorption spectra (including effects of Mie and Rayleigh Scattering) from the VUV to microwave region of the spectrum by Cann in the author's laboratory.

PRINCIPLES AND CONCEPTS

The principles, concepts and history of line-by-line spectral syntheses of emission and absorption spectra of molecules in laboratory, atmospheric and astrophysical situations have recently been reviewed in detail by Nicholls et al. (1986) and Nicholls (1986). Relevant references to past work (referred to above) etc. will be found in these papers.

This paper emphasizes high resolution synthesis of atmospheric extinction (absorption and scattering) spectra, very much in the spirit of "Spectroscopy in the Real World".

In the optically thin situation the Beer-Lambert law for atmospheric transmission I/I_0 holds.

$$I/I_0 = \exp(-\tau) \quad [1a]$$

Where:

I_0 is the incident flux on a slab of thickness X
 I is the emergent flux

The fluxes and the optical depth τ are wavelength dependent. In microphysical terms the optical depth depends on the number density N_i of absorbers/scatterers of various species i in the path and their relevant absorption/scattering cross sections σ through equation [1b]. For solely molecular absorption processes the absorption cross section σ is given by equation [1c] which is written in terms of molecular electronic transitions.

$$\tau = \sum_i X \sum_i N_i \sigma_i(\nu) \quad [1b]$$

$$\sigma_i(\nu) = (8\pi^3/3 hc) \nu R_e^2 (\bar{r}_{\nu,\nu'}) q_{\nu,\nu'} \sum_{\nu'',\nu'''} S_{\nu'',\nu'''} b(\nu) \quad [1c]$$

Where

R_e is the electronic transition moment
 ν is the frequency
 $q_{\nu,\nu'}$ is the Franck Condon Factor
 $r_{\nu,\nu'}$ is the r-centroid
 $S_{\nu'',\nu''}$ is the Honl-London factor
 $b(\nu)$ is the line profile

The summation in equation [1c] is over all spectral features whose wings include the frequency ν . In the case of scattering processes, relevant Rayleigh or Mie expression for σ are used.

Numerical spectral syntheses, which are based on equations [1a,b,c] perform the following functions:

1. Locates line centres of all contributing spectral features.
2. Places a normalized line profile function $b(\nu)$ at the centre of each feature. This may be Gaussian (for thermal broadening), Lorentz (for collision broadening), Voigt (for a superposition of both of these effects), or a more realistic line profile, when known. Wing effects are most important and in realistic spectral syntheses, premature truncation should be avoided. Objective criteria for truncation should be used.
3. Adjusts the amplitude of each function to take account of transition probability and population factors.
4. Selects a grid of ν -values and at each point add the contribution from each line whose profile has a significant value at the point.
5. Depending upon the atmospheric model, and the number of layers used, the output I from one layer is the input I_0 to the next.
6. The resulting table or plot is the high resolution extinction of absorption cross section spectrum. For quantitative comparison with instrumentally recorded spectra it is necessary to degrade the high resolution spectrum by convolution with a suitable instrumental profile. For traditional slit-dispersive spectrometers an appropriate triangle function is often a sufficient representation of the slit function.

It is clear from the above equations that spectral synthesis depends crucially on access to high quality spectral input data on line locations, profiles, and strengths, (transition probabilities). It is a very common misconception that such high quality data are uniformly available. There is a very great need for supporting laboratory programmes to provide the required data.

PAST WORK AT THE CRESS, YORK UNIVERSITY: Realistic High-Resolution, Line-By-Line Syntheses of Atmospheric Transmission Spectra

For more than a decade we have developed a very versatile spectral synthesis facility for simulation of a very broad range of emission and absorption spectra (from the Vacuum ultraviolet to the microwave region of the spectrum) for applications to laboratory, atmospheric and astrophysical situations. This paper briefly reviews the absorption work.

Ultraviolet

High resolution atmospheric transmission (and the resulting high resolution solar spectrum) has been modelled at balloon altitudes (Cann *et al.*, 1979). High resolution transmission of the atmosphere in the region of the NO gamma bands have been modelled (Freedman and Nicholls, 1980). High pressure (to 50 atm) and high temperature (to 3000 K) absorption cross sections of O₂ have been simulated (Cann *et al.*, 1984).

Visible

Atmospheric transmission between 6000-7800 Å has been calculated for application to satellite remote sensing of solar excited fluorescence of ocean algal chlorophyll (Cann *et al.*, 1982; Nicholls, 1986 and see Fig. 1).

Infra-Red

The Burch form factor for the spectral line shapes of the CO₂ 4.3 µm band have been deduced from two sets of high-resolution laboratory measurements on self broadened N₂ and O₂ broadened CO₂ between 0.25 and 3 atm. over a spectral range 3.7 to 4.25 µm at a resolution of 0.0037 µm (Cann *et al.*, 1985a). The resulting spectrum was used to simulate a number of NRL long path (6 km) atmospheric transmission spectra. Excellent agreement was obtained (Roney *et al.*, 1981; Cann *et al.*, 1985a). Detailed examples of CO₂ spectra were presented at the meeting to illustrate what simulations can be made for typical radiatively active gases (see Figs 2, 3 & 4).

Microwave

For applications to satellite remote sensing of the earth's surface, including passive microwave remote sensing of ice and snow, a programme of simulation of the microwave transmission spectrum of the atmosphere is in progress (Cann *et al.*, 1985b).

This spectral synthesis facility is currently being repackaged for portability and ease of use outside our centre. It is planned to make it menu-driven and usable on such dedicated computer facilities as a Micro VAX.

Figures

Figures 1-4. illustrate realistic spectral syntheses in the visible and infrared. Other examples are found in the cited references.

Fig. 1. is a realistic medium-resolution synthesis of the vertical atmospheric transmission spectrum in the yellow-red spectral regions. Absorption features of O_2 , O_3 and H_2O are present.

Fig. 2. shows high-resolution syntheses of the CO_2 , $4.3\ \mu m$ band at one atm total pressure, CO_2 partial pressure 20 torr for 0.1 and 8.0 m paths. The 8.0 m spectrum is saturated.

Fig. 3. is a comparison between the experimental CO_2 transmittance measurements by Buijs for 10 metre atmospheres of CO_2 at a pressure of 0.25 atm and at 294 K. Syntheses based on Lorentz-Winters-Silverman-Benedict (WSB) profiles are included.

Fig. 4. displays part of the infrared radiance spectrum at sea level of a methane flame 16 km distant. The upper curve is the methane flame radiance, and the lower curves are the methane radiance at 16 km and the absorption spectrum of the atmosphere, respectively.

CONCLUSIONS

1. Realistic spectral synthesis is a very powerful diagnostic tool, (when properly used) for interpretation of field measurements of atmospheric transmission spectra.
2. For confident application of the method, basic spectroscopic constants for the molecular species and their feature must be used.
3. For the purpose of studying the RAGS problem, patrol programmes for observation of long path atmospheric transmission spectra should be established. Either dispersed spectra or gas filter correlation spectrometer observations could be used.

REFERENCES

- Cann, M.W.P., Nicholls, R.W., Evans, W.F.J., Kohl, J.L., Kurucz, R., Parkinson, W.H. & Reeves, E.M. (1979). High resolution atmospheric transmission calculations down to 28.7 km in the 200-243 nm spectral range. Applied Optics, 18: 964-977.
- Cann, M.W.P., Miller, J.R., Nicholls, R.W. & Peterson, R.N. (1982). The effects of the atmosphere., Ch.2 in Investigation of the Feasibility of Mapping Chlorophyll Fluorescence from Space., Final Report, DSS Contract Serial OS681-0029 1982.
- Cann, M.W.P., Shin, J.B. & Nicholls, R.W. (1984). Oxygen absorption in the spectral range, 180-300 nm for temperatures to 3000K and pressures to 50 atm. Canadian Journal of Physics, 62: 1738-1751.
- Cann, M.W.P., Nicholls, R.W., Roney, P.L., Blanchard, A. & Findlay, F.D. (1985a). Spectral line shapes for carbon dioxide in the 4.3 μm band. Applied Optics, 24: 1374-1384.
- Cann, M.W.P. & Nicholls, R.W. (1985b). Theoretical computations of the microwave transmittance and emittance in the earth's atmosphere: atmospheric slant path calculations. Pp. 39 in the 11th quarterly Report DSS/AES Contract OES81-00214.
- Freedman, R. & Nicholls, R.W. (1980). Transmission of the atmosphere in the region of the NO gamma bands. Can. J. Physics. 58: 1424.
- Nicholls, R.W. (1986). Realistic synthesis of atmospheric and interstellar extinction spectra. Journ. Quant. Spect. Rad. Trans., S.S. Penner Festschrift issue (in press).
- Nicholls, R.W., Cann, M.W.P. & Shin, J.B. (1986). Realistic numerical syntheses of shock excited molecular spectra. Pp.65-76 in Shock Waves and Shock Tubes., (Ed. D. Bershadan & R. Hanson), Proc. 15th Int. Symp. on Shock Waves & Shock Tubes, Berkeley 1985 July, Stanford University Press.
- Roney, P.L., Findlay, F.D., Blanchard, A., Cann, M.W.P. & Nicholls, R.W. (1981). Atmospheric transmittance in the region near the 4.3 μm band head of CO_2 . Optics Letters, 6: 151.

ATMOSPHERIC TRANSMISSION
DEGRADED WITH 0.50 NM HALF-WIDTH (FWHM)

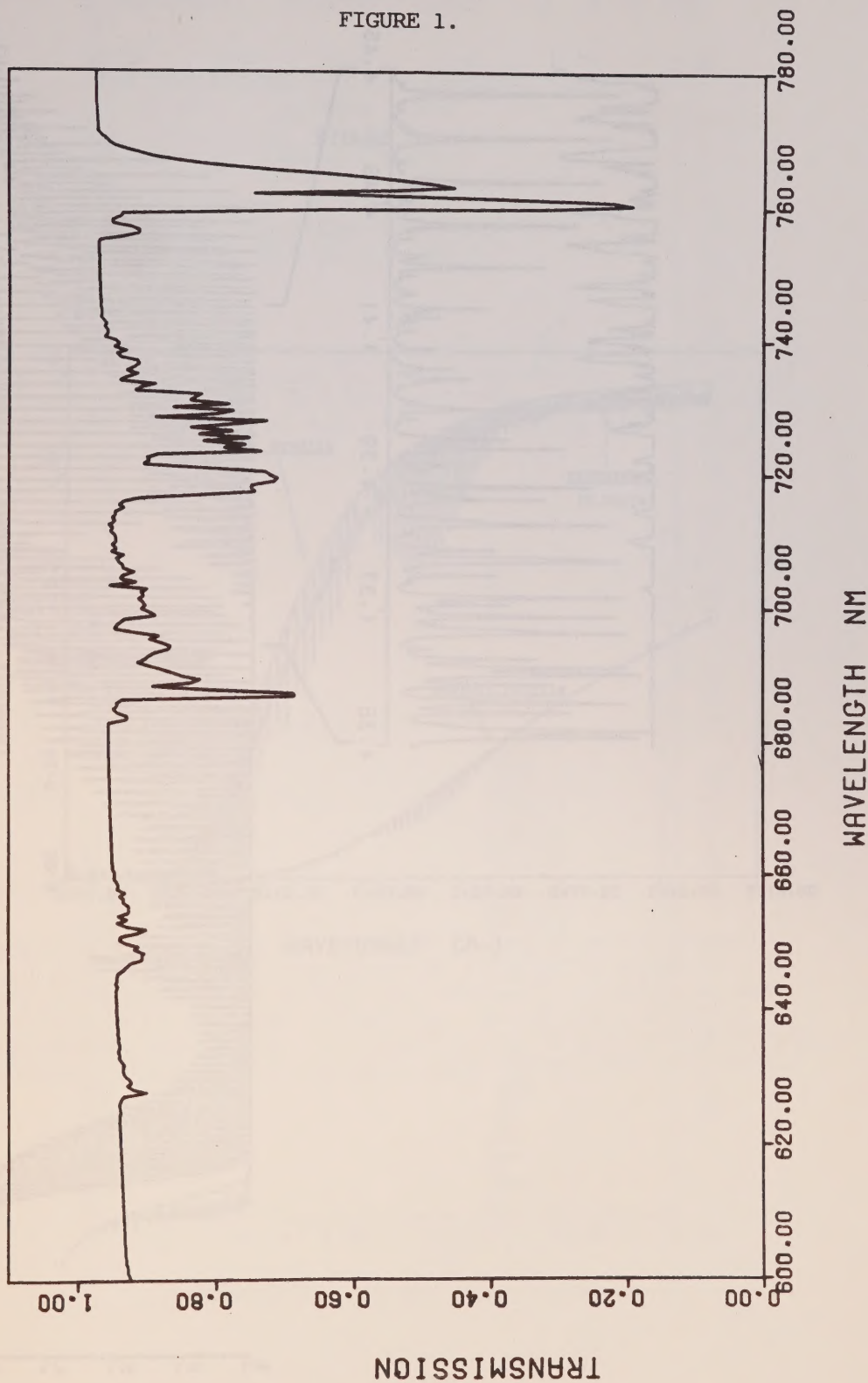


FIGURE 2.

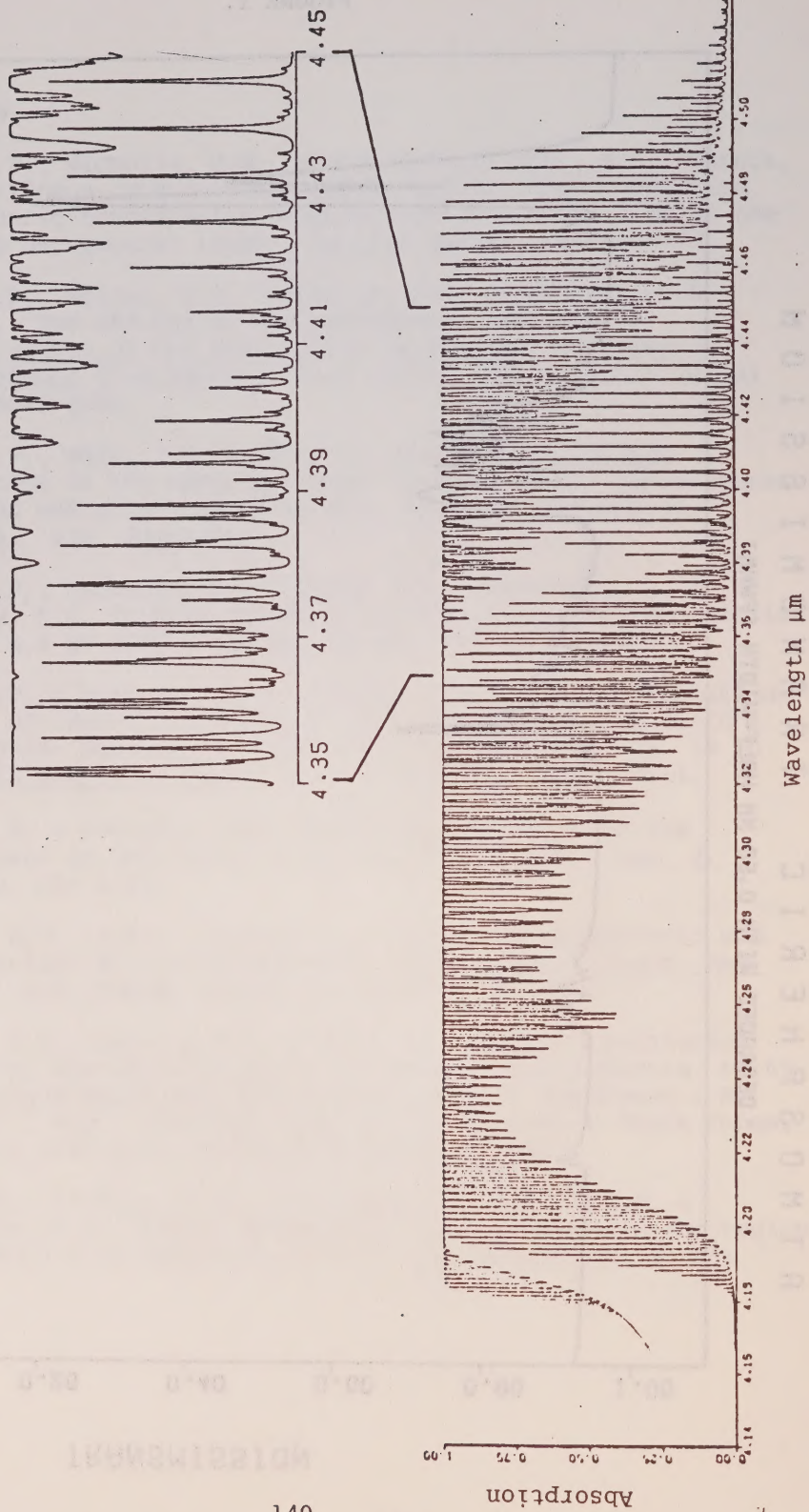
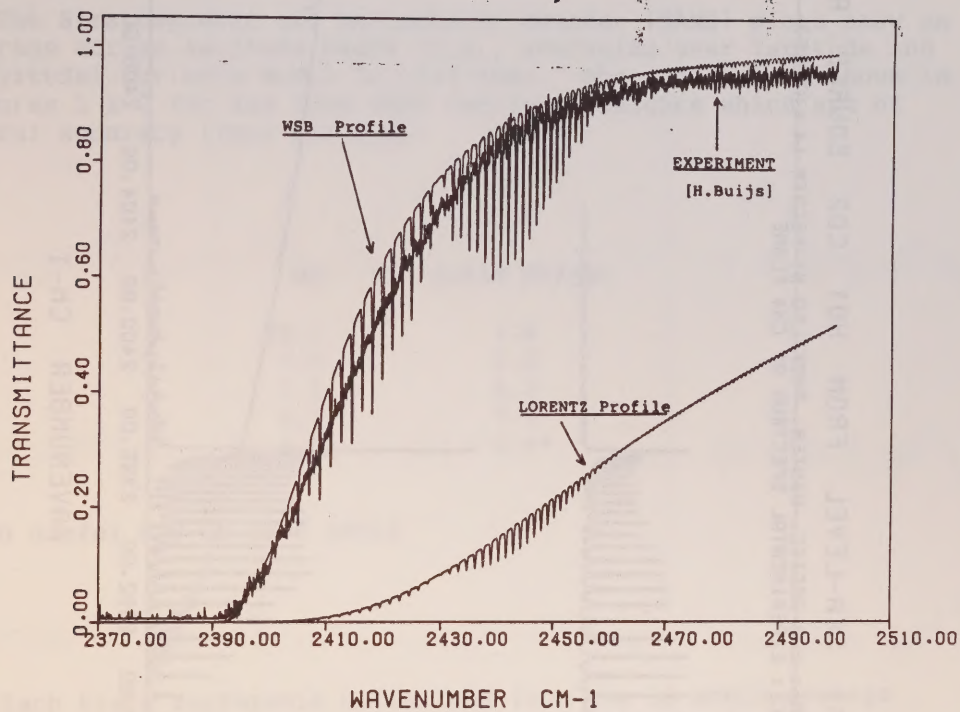


FIGURE 3.



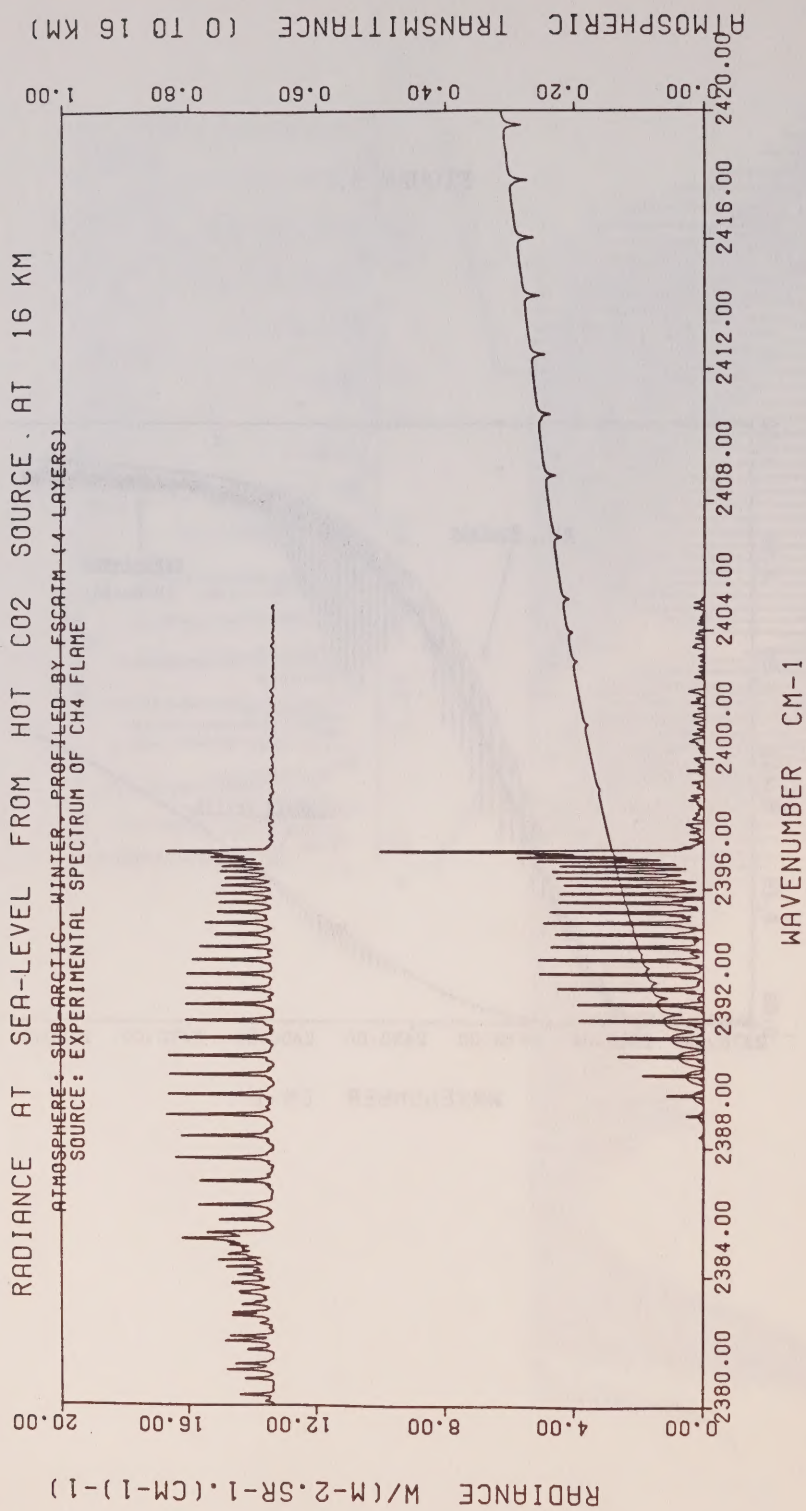


FIGURE 4.

The Stratospheric and Mesospheric Sounder (SAMS) Plots

Howard Roscoe

Department of Atmospheric Physics
Clarendon Laboratory
Oxford University

The Stratospheric and Mesospheric Sounder (SAMS) plots show an average across latitude bands (i.e., averaging over latitude and longitude) for each month in 1979-1981. The results are shown in Figures 1 & 2 for the five SAMS retrieval heights which are of useful accuracy (four for N_2O).

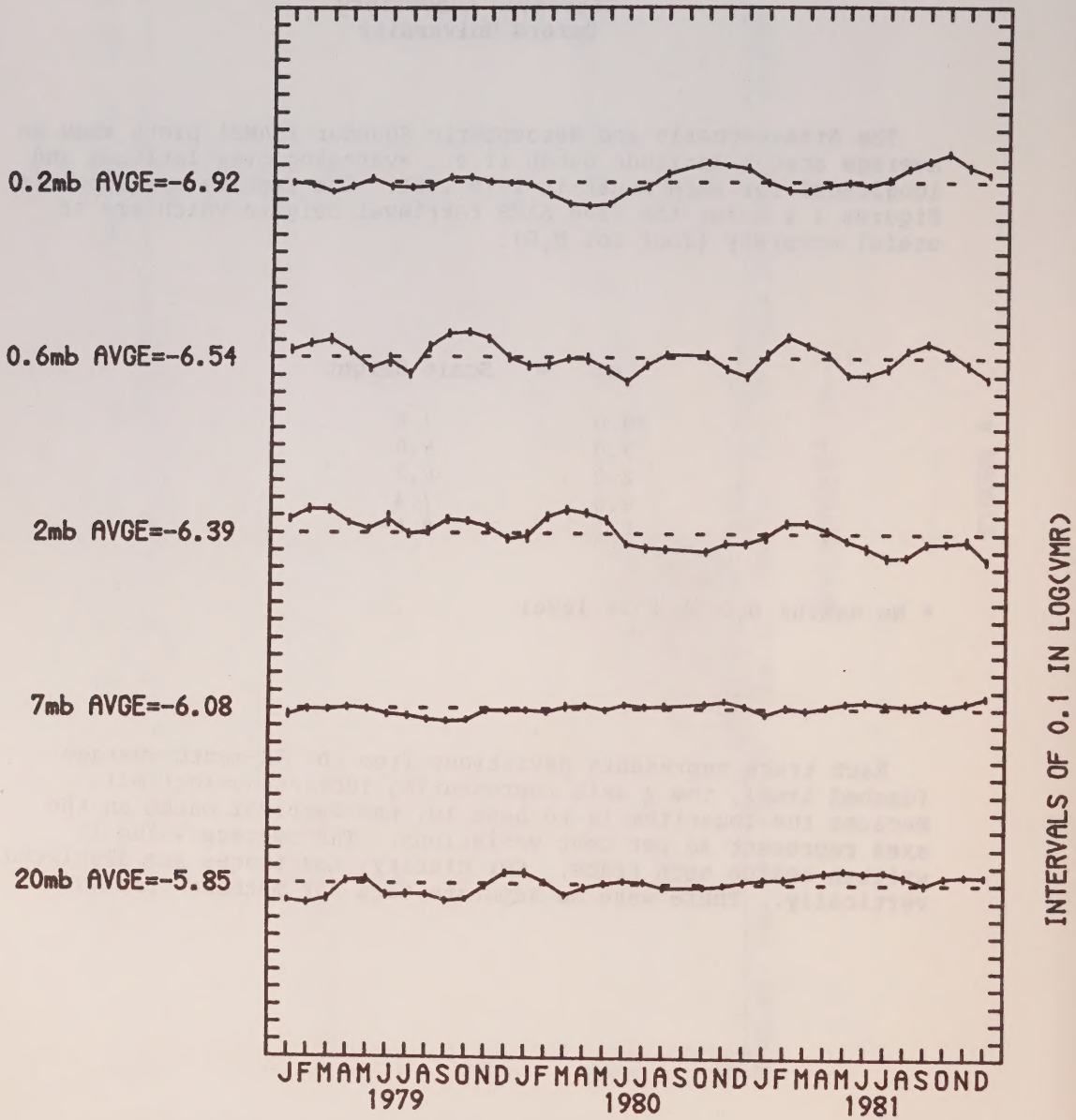
mb	=	Scale Height
20.0		3.8
7.0		5.0
2.0		6.2
0.6		7.4
0.2		8.6*

* No useful N_2O at this level

Each trace represents deviations from the 36-month average (dashed line), the y axis representing increasing $\log(vmr)$. Because the logarithm is to base 10, the vertical marks on the axes represent 30 per cent variations. The average value is written beside each trace. For clarity, the traces are displaced vertically. There were no separate data for methane from 1984.

FIGURE 1.

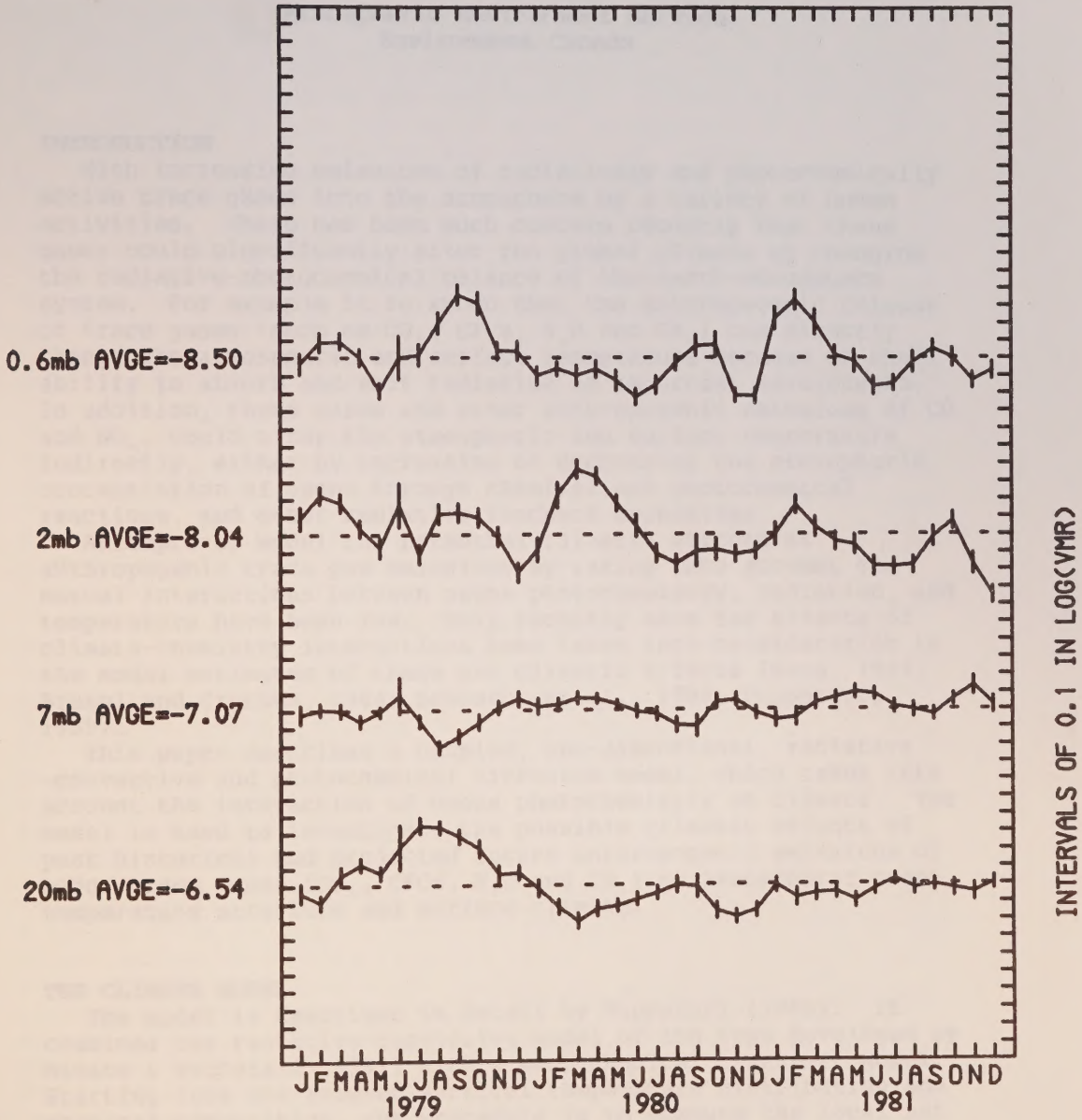
SAMS MEAN CH4 LOG(VMR) 50S-70N



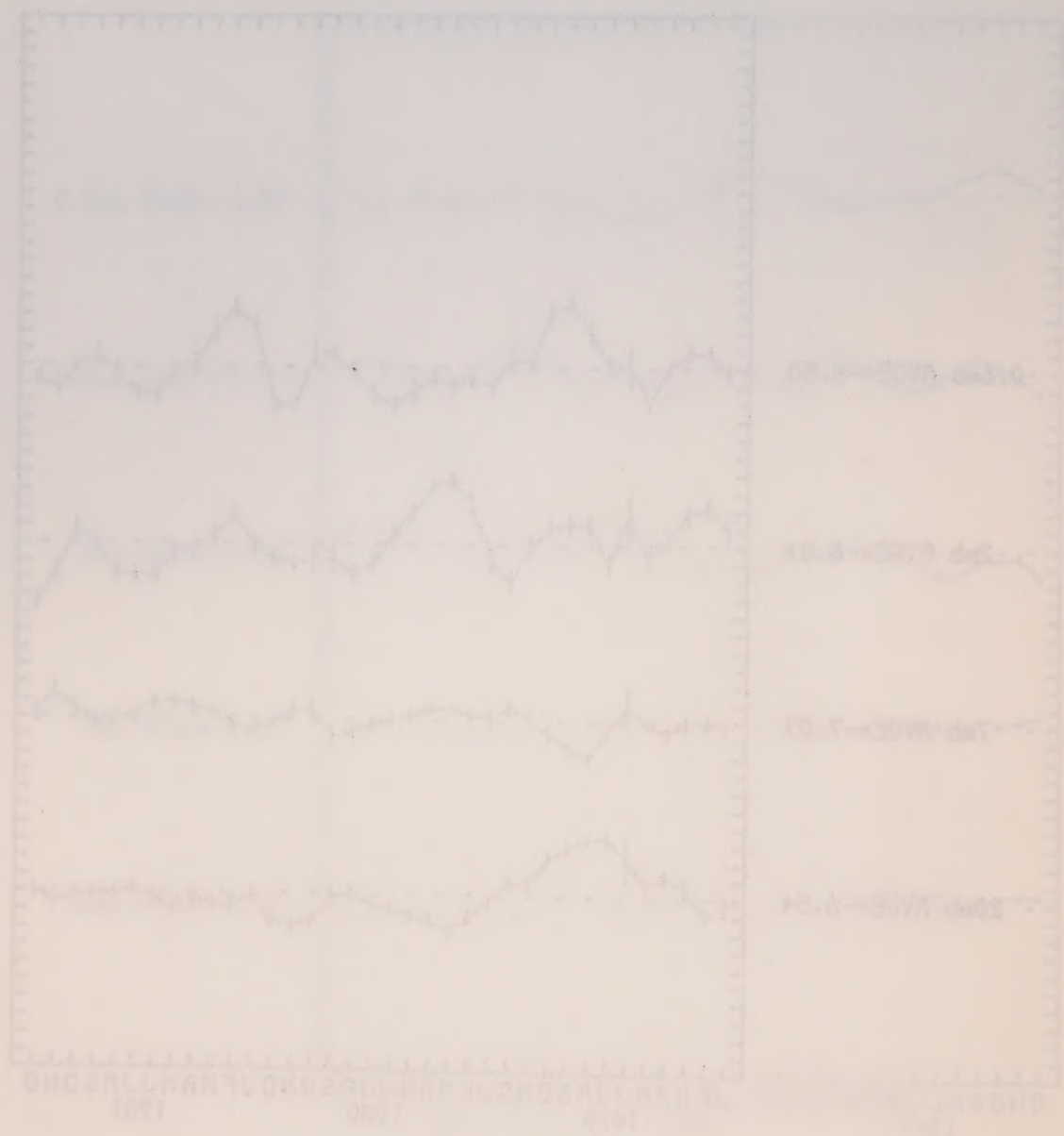
INTERVALS OF 0.1 IN LOG(VMR)

FIGURE 2.

SAMS MEAN N2O LOG(VMR) 50S-70N



70N-50S (1979-2002) MEAN NSO LOG(VMR) 50S-70N



Potential Effects of Anthropogenic Trace Gas Emissions on Atmospheric Ozone, Temperature Structure and Surface Climate

R.K.R. Vupputuri

Atmospheric Environment Service
Environment Canada

INTRODUCTION

With increasing emissions of radiatively and photochemically active trace gases into the atmosphere by a variety of human activities. There has been much concern recently that these gases could significantly alter the global climate by changing the radiative-photochemical balance of the earth-atmosphere system. For example it is known that the anthropogenic release of trace gases (such as CO_2 , CFCs, N_2O and CH_4) can directly change the atmospheric and surface temperature because of their ability to absorb and emit radiation at important wavelengths. In addition, these gases and other anthropogenic emissions of CO and NO_x , could alter the atmospheric and surface temperature indirectly, either by increasing or decreasing the atmospheric concentration of ozone through chemical and photochemical reactions, and other radiative feedback mechanisms.

Attempts to model the potential climatic effects of anthropogenic trace gas emissions by taking into account the mutual interactions between ozone photochemistry, radiation, and temperature have been few. Only recently have the effects of climate-chemistry interactions been taken into consideration in the model estimates of trace gas climatic effects (Wang, 1984; Bruehl and Crutzen, 1984; Brasseur *et al.*, 1985; Vupputuri, 1985).

This paper describes a coupled, one-dimensional, radiative-convective and photochemical diffusion model, which takes into account the interaction of ozone photochemistry on climate. The model is used to investigate the possible climatic effects of past historical and projected future anthropogenic emissions of major trace gases (CO_2 , CFCs, N_2O and CH_4) on atmospheric ozone, temperature structure and surface climate.

THE CLIMATE MODEL

The model is described in detail by Vupputuri (1985). It combines the radiative-convective model of the type developed by Manabe & Wetherald (1967) with a photochemical transport model. Starting from the assumed vertical temperature distribution and chemical composition, the procedure is to compute the local net radiative heating, cooling, photochemical sources and sinks at each altitude to determine the vertical temperature and trace constituent structure with a time-marching method. The upward

heat transfer by atmospheric motions is taken into account implicitly by a simple numerical procedure called convective adjustment which was first introduced by Manabe & Strickler (1964).

THE RADIATIVE TRANSFER MODEL

The solar radiation code used to compute the short-wave solar heating within the atmosphere is based on the delta-Eddington method which is computationally efficient and fairly accurate (Joseph *et al.*, 1976). It considers the absorption and scattering by atmospheric gases (H_2O , CO_2 , O_3 and NO_2), aerosols and cloud droplets. To compute the infrared cooling due to H_2O , O_3 and CO_2 , the analytical formulae for the mean transmissivities of finite frequency intervals derived by Kuo (1979) have been adopted. The mean transmission functions take into account the temperature effect and overlapping absorption between gases and the computed transmissivities have been shown to be in good agreement with line-by-line calculations. For other trace gases such as N_2O , CH_4 and CFCs, the empirical expressions for the mean band absorptivities based on laboratory and spectroscopic data (Burch *et al.*, 1962; Ramanathan *et al.*, 1985) were adopted. Also considered in long-wave calculations are the heating or cooling rate contributions in the atmospheric window band. Both the IR and solar radiation codes have been validated by comparing them against other standard radiation codes and by participating in ICRCM workshop.

THE PHOTOCHEMICAL MODEL

The photochemical system considered for this study includes the important reactions affecting the concentration of ozone and other relevant trace constituents in the atmosphere above 10 km (due to inadequate understanding of complex reactions associated with O_3 , NO_x , CO and hydrocarbons in the troposphere, the chemistry is fixed in that region by prescribing the ozone concentration below 10 km). The chemical species considered are O_x (O , $\text{O}(^1\text{D})$, O_3), HO_x (H , HO , HO_2), NO_x (N , NO , NO_2 , HNO_3), CH_4 , N_2O , CF_2Cl_2 , CFCl_3 and Cl_x (Cl , ClO , ClNO_2). The concentrations of H_2O , CH_4 and H_2 are specified based on observations. The chemical kinetics and photochemical data used are based on the NASA (1985) panel recommendation.

THE TRACE PERTURBATION SCENARIO

The scenario for an increase in trace gases used in the present calculations is similar to the best estimate reported by Ramanathan *et al.* (1985) and is outlined in Table 1. The mixing ratio values of CO_2 , N_2O , CH_4 for the year 1850 correspond to those of the pre-industrial background troposphere and are inferred until present time from available observations. The chlorofluorocarbons CF_2Cl_2 and CFCl_3 whose concentrations are

negligible until 1940, are increased according to their industrial production rates until 1980. The projected increases in the concentration of all these trace gases from the present to the year 2050 are estimated based on the analysis of observed trends in emissions and atmospheric residence times. The tropospheric chemical reactions associated with O_3 , NO_x , CO and hydrocarbons are highly complex and poorly understood. For these reasons the effects of altered chemistry below 10 km are included only implicitly by prescribing the projected O_3 decreases which are believed to be caused by anthropogenic increases in CO and NO_x concentrations.

RESULTS AND DISCUSSION

Equilibrium Calculations

Using the trace gas increase scenario described in Table 1, the coupled one-dimensional radiative-convective and photochemical diffusion model is used to predict first the equilibrium atmospheric vertical temperature and trace constituent structure interactively and self consistently for the years 1850, 1980 and 2050. The dash dot curves in Figs. 1 and 2 show the computed atmospheric and surface temperature changes under equilibrium conditions for the periods 1850 to 1980 and to 2050 respectively (Fig. 3). Also shown in Figs. 1 and 2, for comparison, are the atmospheric and surface temperature changes due to increases in CO_2 concentration alone (solid curve) and CO_2 plus all other major trace gases (dashed curve) using standard atmosphere ozone profile (no temperature-chemistry coupling). It is seen from Fig. 3 that the trace gas increase scenario adopted in this study leads in general to a net ozone decrease in the middle and upper stratosphere and an increase in the lower stratosphere and troposphere and as shown in Figs. 1 and 2 (dash dot curves). These changes in the vertical ozone distribution are reflected in atmospheric and surface temperature changes. It is clear from Figs. 1 and 2 that the direct (radiative) and indirect (resulting from radiative photochemical interactions) climatic effects of major trace gas increases other than CO_2 contribute substantially to the computed CO_2 warming at the surface. For example, the increase in the CO_2 concentration for the period 1850 to 1980 increases the surface temperature by 0.55 K (solid curve in Fig. 1) which is enhanced by 45 per cent by the direct radiative effects of other major trace gas increases for the same period (dashed curve in Fig. 1). If the indirect temperature effects caused by the net ozone changes (radiative-photochemical interactions) are taken into account the enhancement in CO_2 warming by other major trace gases is further amplified from 45 to 70 per cent (dash dot curve in Fig. 1). It is worth noting that for the period 1980 to 2050, the percentage direct and indirect contributions of other major trace gases to the estimated CO_2 warming at the surface increase significantly. For example, the projected increase in CO_2 concentration for the

year 2050 warms the model surface by 1.75 K which is enhanced by 87 per cent by the direct radiative effects of the major trace increases for the same period and if we add the indirect contributions of ozone changes, the total enhancement by the other trace gases reaches 120 per cent (see Fig. 2).

In the stratosphere the increased loss of energy to space caused by the trace gas increases results in a cooling which increases with altitude (see Figs. 1 & 2). This cooling by the direct radiative effects of trace gases is further enhanced by the indirect effects of net ozone decrease resulting from the radiative-photochemical interactions.

Time-Dependent Calculation

The equilibrium response of the atmosphere to a step-wise increase in the trace gases may not be considered as very realistic because of the long atmospheric lifetimes (~100 years) for some of the trace constituents such as N_2O and chlorofluorocarbons. For this reason, the second experiment was carried out to calculate the transient response of the atmosphere to a time varying trace gas concentration based on the trace gas increase scenario described in Table 1. Because there were no significant changes in any of the trace gases except CO_2 before 1940, the time-dependent calculation is carried out for the 110 year period from 1940 through year 2050 (the step-wise increase in CO_2 concentration was used to establish the equilibrium warming for the year 1940). The time-dependent calculation of the atmospheric response due to major volcanic events such as Agung and El Chichón was also considered.

Figures 4 & 5 show the calculated changes in the surface temperature and total ozone column as a function of time for the time-dependent trace gas increase scenario used in this study. The corresponding variations in the stratospheric temperature and ozone mixing ratio are illustrated in Figures 6 & 7 respectively. It can be seen from Fig. 4 that there is a steady increase in the surface temperature except when it is interrupted by the major volcanic eruptions (Agung and El Chichón) which produce temporary cooling of less than one degree Celsius. The predicted warming at the surface by the year 2050 is about 3.2 Celsius. The variation in the total ozone column indicates that one can expect a small increase (up to 1.5 per cent) until the turn of this century except during the major volcanic eruptions when the total ozone column is expected to decrease (see Fig. 5). After the year 2000, the ozone reductions in the stratosphere due to CFCs increase will dominate the ozone increase in the lower atmosphere resulting in a net ozone column depletion which increases with time rather rapidly as the middle of next century is approached. The expected total ozone column decrease by the year 2050 is around 7.5 per cent.

In the case of the stratosphere, the cooling at 42 km (upper stratosphere) increases steadily almost uninterrupted by the volcanic events and reaches about 20 K by the year 2050. At 25 km (lower stratosphere) the cooling is replaced by warming of

several degrees during the periods of Agung and El Chichón volcanic eruptions (see Fig. 6). The stratospheric ozone variation is similar to that of temperature. At 42 km the ozone mixing ratio increases slightly at first and after 1960 it decreases steadily without being interrupted by the volcanic events to almost 50 per cent by the year 2050. At 25 km, the Agung and El Chichón eruptions cause the ozone mixing ratio to decrease by 5 to 6 per cent and this is reflected in the total ozone column variations in shown in Fig. 5.

CONCLUSIONS

Despite the neglect of certain radiative-dynamic feedback processes and uncertainties in the estimates of projected trace gas increases, the results based on this coupled, one-dimensional radiative-convective and photochemical diffusion model show the direct and indirect climatic effects of major trace gases, other than CO_2 , contribute substantially to the long term atmospheric and surface changes in temperature. These are caused by an increase in CO_2 . Equilibrium calculations indicate that by the year 2050, the estimated warming of about 1.8 K due to CO_2 increase will be enhanced by more than 100 per cent by the direct and indirect climatic effects of increased emissions of other major trace gases. The atmospheric response to these increases in trace gases suggests that surface temperature increases steadily to a value of 3.25 C by the year 2050. Major volcanic events can cause a temporary cooling of less than one degree. The time-dependent calculations also suggest that a small increase in the total ozone column until the year 2000 can be expected, except during major volcanic events when the ozone increase is temporarily replaced by a decrease. After the year 2000, the total ozone column is expected to decrease rather rapidly to value of 7.5 per cent as the year 2050 is approached. Better spectroscopic, chemical kinetic, photochemical data and improved understanding of the trace gas trends and climate-chemistry interactions in the troposphere will help to determine more accurately the direct and indirect effects of increased CO_2 and other trace gases on the climate.

REFERENCES

- Bruehl, Ch. & Crutzen, P.J. (1984). A radiative convective model to study the sensitivity of climate and chemical composition to a variety of human activities. Proceedings of a Working Party Meeting, Brussels, May 1984 (Edited by A. Ghazi).
- Brasseur, G., Rudder, A.D. & Tricot, C. (1985). Stratospheric responses to chemical perturbations. J. Atmos. Chemistry, 3: 261-288.

- Burch, D.E., Grynak, D., Singleton, D., France, W.L. & Williams, D. (1962). Infrared Absorption by CO₂, H₂O and Minor Atmospheric Constituents. AFCRL-62-688, Ohio State U. Contract AF19 (604)-2633.
- Joseph, J.H., Wiscombe, W.J. & Weiman, J.A. (1976). The delta-Eddington approximation for radiation flux transfer. J. Atmos. Sci., 33: 2452-2459.
- Manabe, S. & Strickler, R.F. (1964). Thermal equilibrium of the atmosphere with a convective adjustment. J. Atmos. Sci., 21: 361-385.
- Manabe, S. & Wetherald, R.T. (1967). Thermal equilibrium of the atmosphere with a given distribution of relative humidity. J. Atmos. Sci., 24: 241-259.
- NASA (1985). Chemical Kinetics and Photochemical Data for Use in Stratospheric Modelling. Panel for Data Evaluation. Pub. 85-37, Jet Propul Lab., Pasadena, Calif., 1985.
- Ramanathan, V., Singh, H.B., Cicerone, R.J. & Kiehl, J.T. (1985). Trace gas trends and their potential role in climate change. J. Geophys. Res., 90: 5547-5566.
- Rotty, R.M. & Marland, G. (1980). Constraints on carbon dioxide production from fossil fuel use. Proc. of Energy/Climate Workshop: Munster, Germany, March, 1980.
- Vupputuri, R.K.R. (1985). The effect of ozone photochemistry on atmospheric and surface temperature changes due to increased CO₂, N₂O, CH₄ and volcanic aerosols in the atmosphere. Atmosphere-Ocean, 23: 359-374.
- Wang, W.C. (1984). Climatological effects of atmospheric ozone: a review. Atmospheric Ozone, Proc. of the Quadrennial Ozone Symposium, Greece, September 1984.
- Weiss, R.F. (1981). The temporal and spatioal distribution of tropospheric nitrous oxide. J. Geophys. Res., 86: 7185-7195.

Trace Gas	Year 1850 Mixing Ratio (ppbv)	Year 1980 Mixing Ratio (ppbv)	Year 2050 Mixing Ratio (ppbv)	Remarks
CO ₂	270×10^3	339×10^3	502×10^3	Rotty and Harland (1980)
N ₂ O	283	300	410	Weiss (1981)
CH ₄	1.15×10^3	1.65×10^3	2.78×10^3	Assumes 0.75% increase between 1980 and 2050
CFC-12	0.0	0.45	3.0	Assumes 3% per year growth rate
CFC-11	0.0	0.25	1.5	Assumes 3% per year growth rate
O ₃	Standard profile	12.5% increase	33% increase	Ramanathan et al. (1985)

TEMPERATURE CHANGE DUE TO TRACE GASES FOR THE PERIOD 1850 TO 1980

- CO₂ only with fixed ozone
- - - - CO₂ + N₂O + CH₄ + CFC'S with fixed ozone
- · - · CO₂ + N₂O + CH₄ + CFC'S with variable ozone

Table 1. Estimates of Trace Gas Concentrations in the Atmosphere

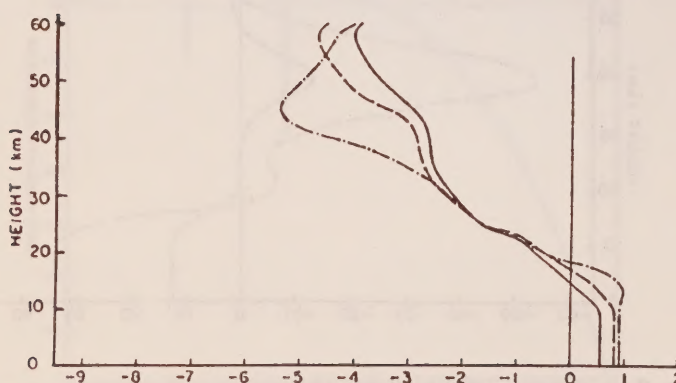


Figure 1. Temperature Change (C) Computed Changes in Atmospheric and Surface Temperature 1850-1980 due to CO₂ Alone and to CO₂ Plus all Other Major Trace Gases With and Without O₃ Photochemical Interaction

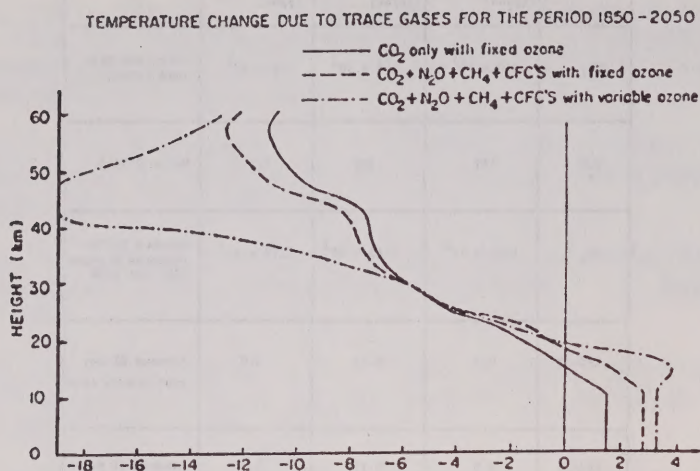


Figure 2. Temperature Change (C) Computed Changes in Atmospheric and Surface Temperature 1850-2050 due to CO_2 Alone and to CO_2 Plus all Other Major Trace Gases With and Without O_3 Photochemical Interaction

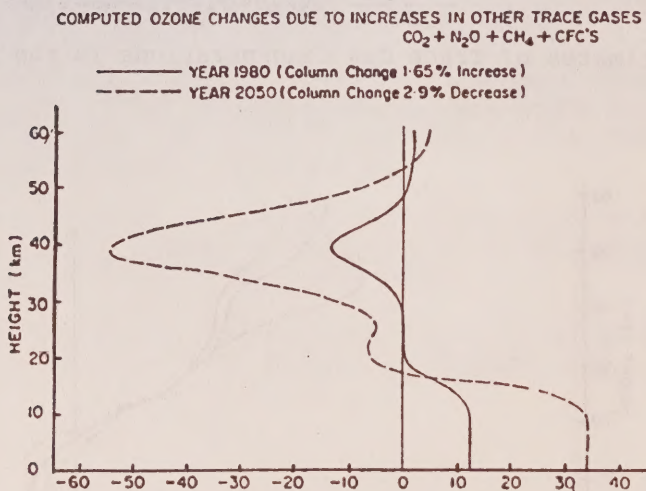


Figure 3. Computed changes in Atmospheric O_3 for the Periods 1850-1980 & 1850-2050 due to an Increase in CO_2 Plus All Other Major Trace Gases

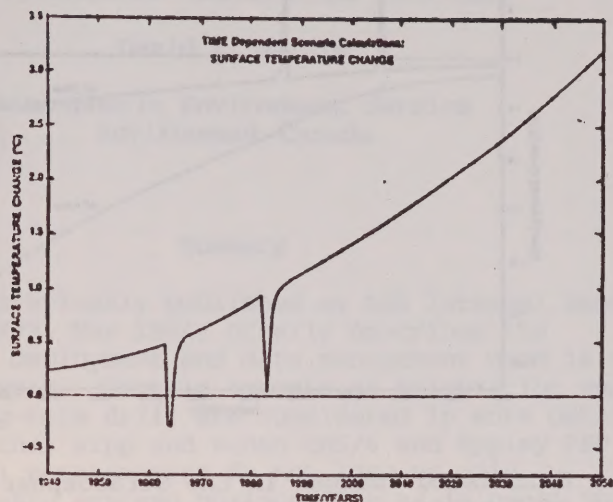


Figure 4. Calculated changes in Surface Temperature (C) as a Function of time for the Varying Trace Gas Increase Scenario Adopted in This Study

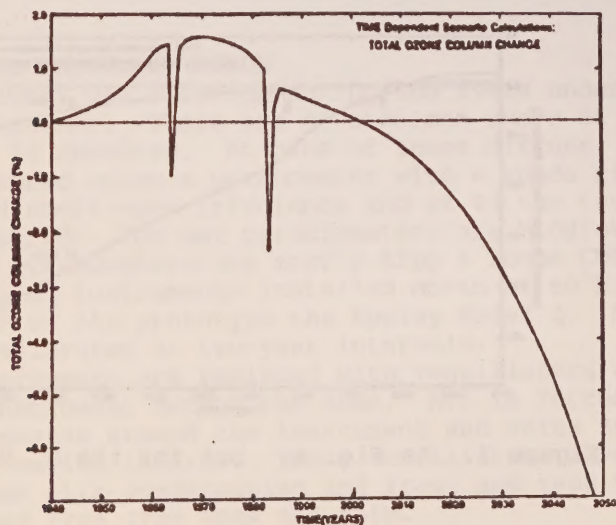


Figure 5. As Fig. 4 but for the Total O_3 Column

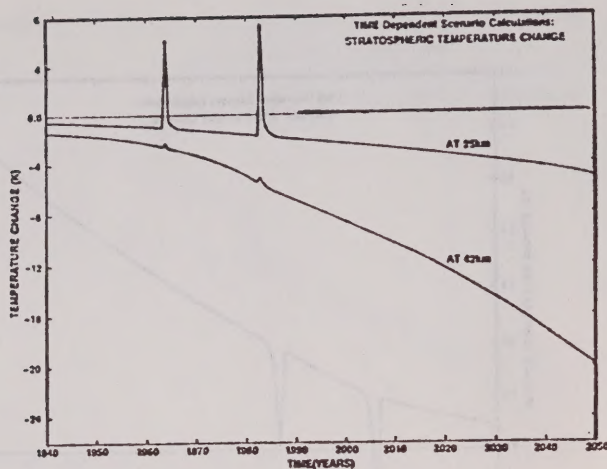


Figure 6. Calculated Changes in the Stratospheric Temperature as a Function of Time for the Time Varying Trace Gas Increase Scenario Adopted in this Study

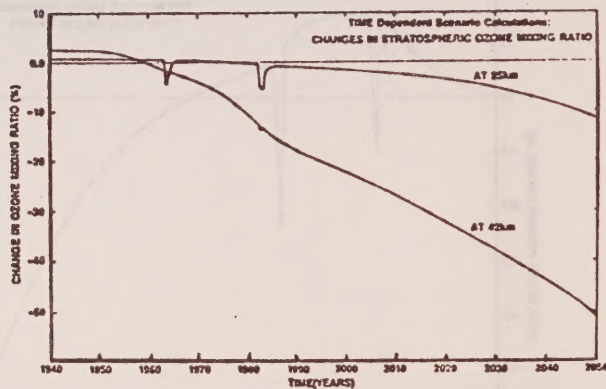


Figure 7. As Fig. 6. but for the O_3 Mixing Ratio

The Canadian Radiation Network and Long Term Records of Pyranometer Calibration 1960-1984

David I. Wardle

**Atmospheric Environment Service
Environment Canada**

Summary

This paper (previously published as AES Internal Report No. APRB 116X39, May 1984) briefly describes the instruments, deployment and data management used in the Canadian Network. Certain aspects of calibration and possible long-term drift are considered in more detail. It is shown that Kipp and Zonen CM5/6 and Eppley PSP (and Model 2) pyranometers do not lose or gain sensitivity when exposed horizontally as is usual in meteorological monitoring. A steadily increasing and ultimately large error during the 1970s in the Kipp and Zonen manufacturer's calibration factors is identified. Also, a difference of about 3 per cent between the Eppley calibration factors and the Canadian values is evident for most of the period.

NETWORK: EXTENT AND INSTRUMENTATION

The present network was built up during the 1960s under the direction of J.R.Latimer. There are 49 stations where at least global irradiance is measured. At nine of these diffuse irradiance is measured using a pyranometer with a shade ring, at five the reflected short-wave irradiance and at 23 the total net radiation are measured. The net pyradiometers are Middleton CN2s (Funk type). The pyranometers are mostly Kipp & Zonen CM5s, except for the global instruments installed north of 60°N. These are the Eppley PSP or its prototype the Eppley Model 2. All instruments are calibrated at two-year intervals.

The global instruments are equipped with ventillators which enclose all the instrument except the dome. Air is forced up from below, then passes around the instrument and exits at the base of the dome, moving inwards. These ventillators have almost eliminated problems with condensation and frost and tend to keep the domes clean and free from snow and rain.

DATA MANAGEMENT

The data are recorded on-site as hourly integrations based on local solar time using a printing ball and disc integrator; a chart recording is also made and used for quality control. The chart recording and printout from the integrator are sent to the AES very month where they are scrutinized for timing errors, effects of dew, frost or snow on the sensor domes or shadows of local objects. Appropriate corrections are made to the hourly integrations. Some further quality control is done automatically by comparison with computed clear-sky values.

The diffuse irradiance is evaluated using a calibration factor which is set for each month so that on fully overcast days in that month the diffuse total is equal to the global total. There is also a crude but small correction made for the non-isotropic radiance distribution in clear conditions. An amount $f \times 2\%$ is added to all diffuse measurements on any particular day where f is the fraction of that day during which it was sunny. The measurements have been published in the AES Monthly Radiation Summary since 1960.

The data management system will be replaced during 1986. The quality control techniques in the new system will include the inspection of daily data on a high resolution display (1 minute $\times$ 2 W.m^{-2}) by experienced personnel.

RADIATION STANDARDS AND CALIBRATION

The National Atmospheric Radiation Centre (NARC), which is a WMO regional radiation centre, maintains the standard pyrheliometers, calibrating pyrheliometers, and calibrating pyranometers. The pyranometer calibrations depend on the NARC pyrheliometers which are often compared among themselves and have been taken to several international pyrheliometer comparisons (IPC II, 1964; IPC III, 1970; IPC IV, 1975; IPC V, 1980 - all in Switzerland - and to the Table Mountain Washington comparisons in 1959 and 1960).

Table 1. lists the more important standard pyrheliometers used by NARC during the past 25 years. It also shows when each instrument may have been used as the primary standard for the NARC.

TABLE 1.

**Important Standard Pyrheliometers Used Since 1960
By The National Atmospheric Radiation Centre**

Manufacturer & Serial No.	Acquired By NARC	Origin Of The Calibration	Used As NARC Prime Standard
Hickey-Frieden #18747	1979	Manufacturer's absolute	1979-present
Eppley-Kendall #11399	1972	Manufacturer's absolute	1974-1979
Eppley-Angstrom EA9001	1968	Eppley	---
Abbot silver disc T7	1964	from SI14 confirmed by PACRAD* at IPC III	1971-1974
SMHI-Angstrom A210, A208	1960	Manufacturer (Stockholm)	---
Lindblad-Angstrom Al49, Al50	1954	Manufacturer (Stockholm)	---
Smithsonian silver disc SI14 (repaired 1960)	1937	from Table Mountain SI5# in 1960	1960-1965

* The primary absolute cavity radiometer of J.M.Kendall.

Smithsonian Institution Silver-Disk #5

The relation of these standards to the current World Radiometric Reference can be summarized as follows:

1. From the present back to 1970/06/01 the standards were within 0.3 per cent of the WRR.
2. Between 1970/06/01 and sometime early in 1965 (probably January) the standard was $1.25 \pm 0.3\%$ (2σ) lower than WRR.
3. Prior to 1965 the standard was $0.25 \pm 0.6\%$ (2σ) lower than WRR.

With the benefit of hindsight it has been possible to make this a fairly simple summary but, in the past and especially before 1970, the situation was confusing. For example, the Eppley-Angstrom (EA9001) had a manufacturer's calibration that differed by 2.6 per cent from that of the SI14 and the precision of comparison measurements was not as high as that obtainable with today's instruments. It is to the credit of J.R.Latimer, who was then in charge of the NARC, that the standards were kept so constantly (see Latimer, 1973 for a review of the situation in the early 1970s).

PYRANOMETER CALIBRATIONS

Because pyranometers must respond to radiation from a wide range of incidence angles ($\pm \pi/2$), their calibration factors are less well defined and are nearly always less precisely determined than those of pyrhemimeters. For example, a step change of 1.25 per cent, such as occurred in the NARC pyrhemimeter standard, would, until recently, be difficult to recognize in pyranometer calibration.

Since 1970, the Canadian network pyranometers have been calibrated against reference instruments of like manufacture every two years in the NARC diffuse radiation sphere. The pyranometer to be calibrated, together with one or two reference pyranometers, is put into the sphere where all are subject to the same irradiance. The calibration factor is determined as the product of the calibration of the reference pyranometer with the ratio of signals from the tested and reference pyranometers. It is expressed in the units microvolts per watt per square meter ($\mu\text{V.W}^{-1}\text{m}^2$).

The sphere reference instruments (Kipp 2498, Eppley 10037 and 11671) have assigned calibration factors based on many outdoor occultation measurements. The intention was to choose calibration factors suitable for the Canadian Network. This is nominally achieved by taking an average of all calibration measurements between 8 a.m. and 4 p.m. on clear July days from the site at Mt. Kobau (50°N , 1870 m alt.).

The factor for the Kipp reference has been changed occasionally in response either to changes in the pyrhemimeter standard (June 1971) or to a better determination of the calibration factor (September 1974). In the case of the Eppley reference, there was a purely clerical error of 2.3 per cent which was corrected in January 1974.

STABILITY OF PYRANOMETER CALIBRATIONS

Figures 1 & 5 show the relation of the original manufacturer's calibration (KM) to the NARC calibration (KC) of the same pyranometer plotted against the date of the NARC calibration. Most pyranometers are represented by several points each, corresponding to different NARC calibrations over the period 1970-1983. These data are derived using today's (post 1974)

calibration factors for the reference instruments. The actual factors in use prior to 1974 are indicated by the thin solid lines and have already been discussed in relation to changes in the pyrheliometer standard, recalibration and the "clerical error". No attempt has been made to modify the manufacturer's factors in relation to the change from IPS to WRR, or for any other reason.

The data are remarkable for the wide spread of discrepancy between those obtained by each manufacturer and by the NARC. The Kipp discrepancies range from -10 to +7 per cent, while those for the Eppley range between -7 & 0 per cent. It may be noticed that before 1974, the NARC "clerical error" caused a fortuitous agreement between NARC and Eppley results.

Figures 2 & 6 show the same data as Figures 1 & 5 but rearranged according to the date of manufacturer's calibration. Figure 2 demonstrates an upward drift of 10 per cent in the Kipp calibration between 1970 and 1980. Figure 7 shows a mean discrepancy of from 3-4 per cent, but no long-term drift. The writer has been informed by Dr. John Hickey that the Eppley reference was changed in 1981 by about 3 per cent, from which it follows that the Eppley NARC discrepancy will probably be smaller in future. As well, the Kipp factory calibration was changed in 1980.

Figures 3,4,7 & 8 have nothing to do with manufacturers' calibration. The ordinate in every case is a NARC calibration factor (KC) on a particular instrument compared with the first NARC calibration (KCO) on that instrument. There are two versions of the abscissa, either the date of the first calibration, or date of any subsequent calibration. In the writer's opinion these four graphs show conclusively that the NARC calibration factors are not drifting.

To investigate the possibility of drift numerically, the sphere calibration data were analysed to estimate a hypothesized linear drift between the field instruments as a group and the reference instruments.

The results are shown in Table 2 which indicates the estimated drifts are in the region of only 1.0 per cent during three years and in opposing directions for the CM5 and PSP. These are very small and it is concluded that the pyranometers used in the Canadian network are not subject to ageing, although clear evidence of ageing has been presented by others (Zerlant,1981). It is probable that ageing only happens when some threshold of temperature and/or irradiance is exceeded for a sustained period. Perhaps these conditions are encountered more often when pyranometers are mounted sloping towards the sun or on solar tracking tables.

TABLE 2.

Drift of References vs. Field Instruments 1970-73

Kipp CM5		Eppley PSP	
682	# Calibrations	289	
219	# Instruments	74	
0.059	Drift in %	-0.064	
+/-0.007	per annum	+/-0.011	
0.45%	RMS Scatter of each calibration	0.49%	

The analysis also yields a value for the effective noise in sphere calibrations (approximately 0.5 per cent, Kipp and Eppley pyranometers). A more obvious measure of the variability of sphere calibrations is given by the discrepancies between each calibration and the previous one (KPO) on that pyranometer. Figures 9 & 10 show the distribution of discrepancies. The histogram display takes no account of the time between successive calibrations which ranges from 2 to 10 years. The rms spreads are 0.7 per cent for the Kipp, and 0.8 per cent for the Eppley pyranometers.

REFERENCES

- Monthly Radiation Summary, Prepared by the Atmospheric Environment Service, Environment Canada. Ottawa: Information Canada.
- Latimer, J.R. (1983). On the Angstrom and Smithsonian absolute pyrheliometric scales and the international Pyrheliometric Scale 1956. Tellus, XXV, 6: 586-592.
- Zerlant, G.A. (1981). Round robin calibrations of selected pyranometers from 1980 Davos comparison. Pp. 104-123 in Proceedings of the IEA Conference on Pyranometer Measurements, SERI/TR-642-1156, 16-20 March 1981, Boulder, Colorado.

FIGURE 1.

CALIBRATION SCATTER PLOT FOR KIPP CM-5/6

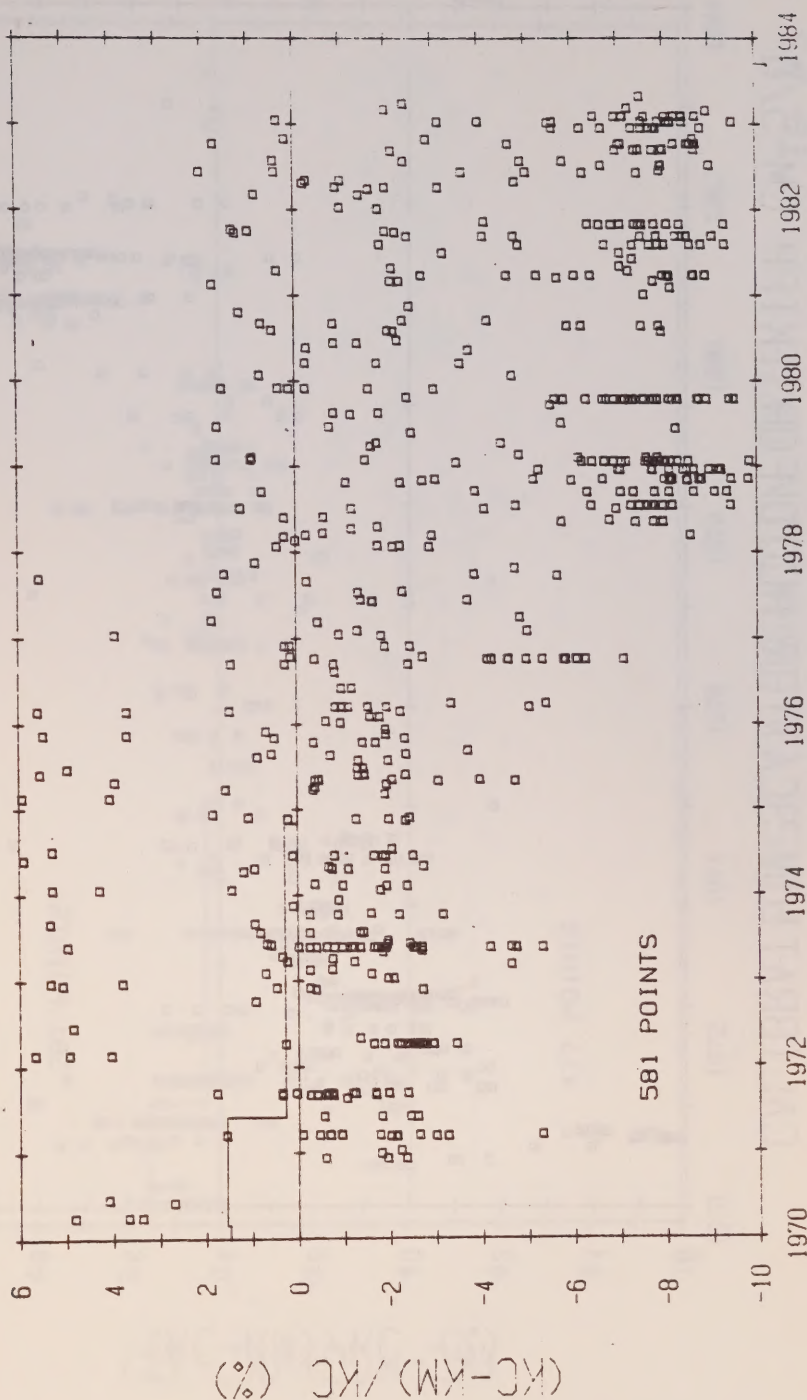


FIGURE 2

CALIBRATION SCATTER PLOT FOR KIPP CM-5/6

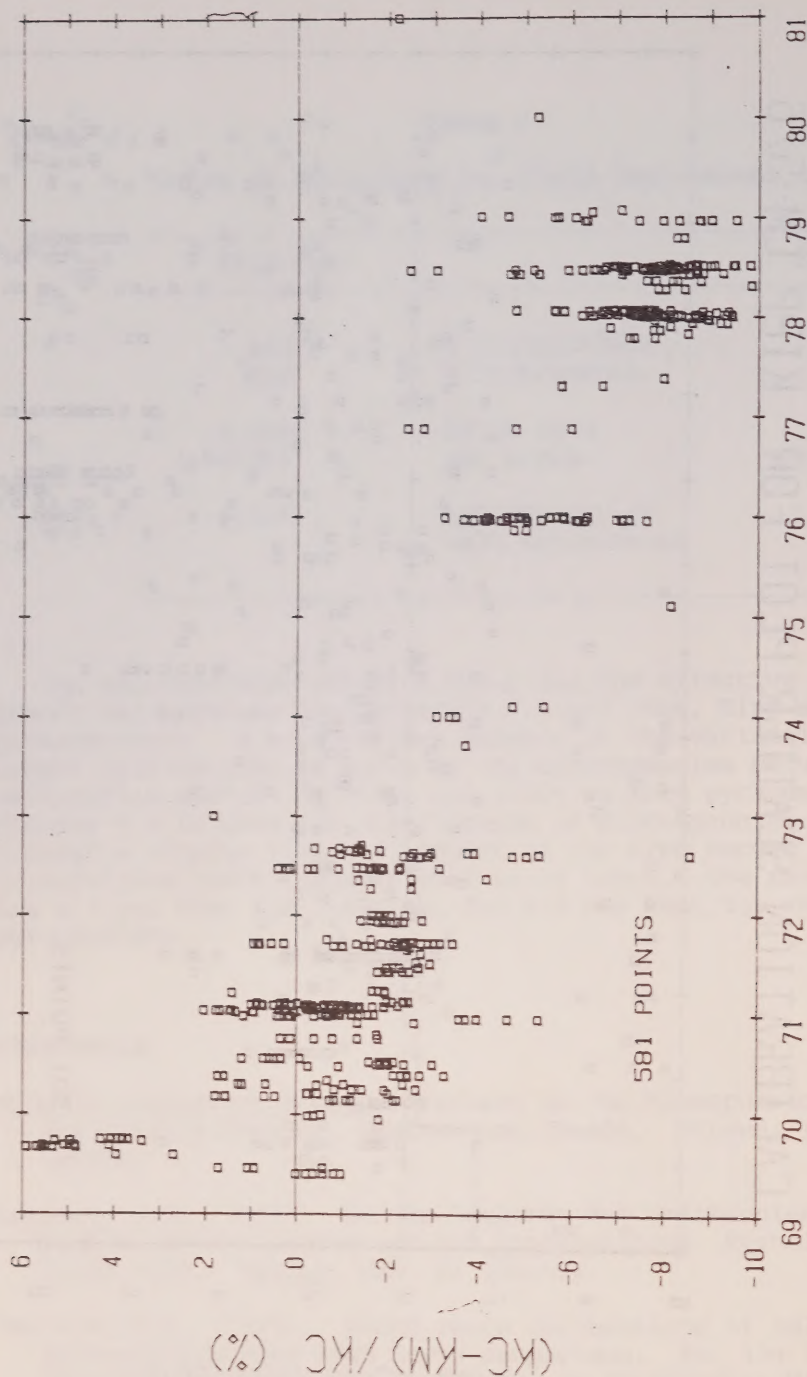
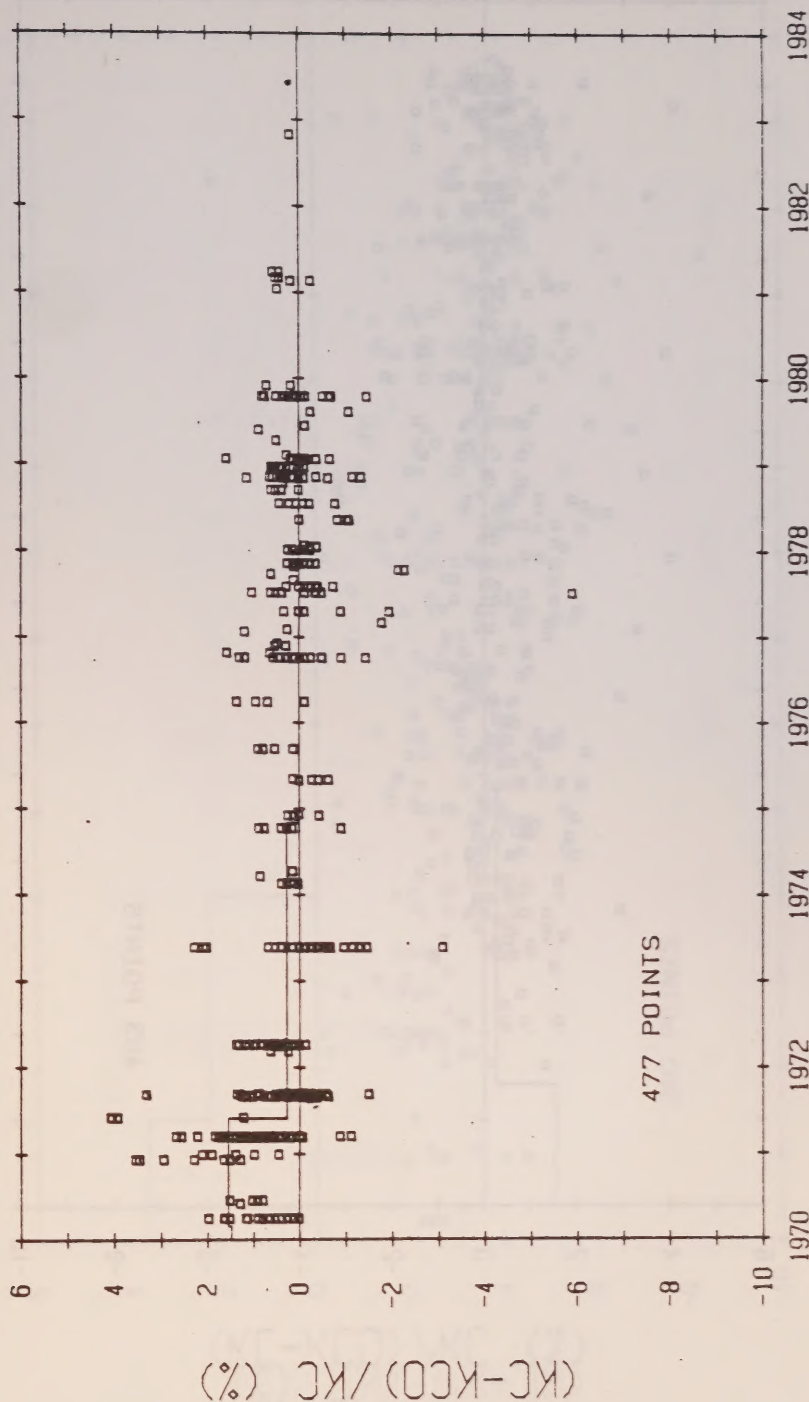


FIG #2

FIGURE 3.

CALIBRATION SCATTER PLOT FOR KIPP CM-5/6



FIRST CALIBRATION DATE FIG #3

FIGURE 4.

CALIBRATION SCATTER PLOT FOR KIPP CM-5/6

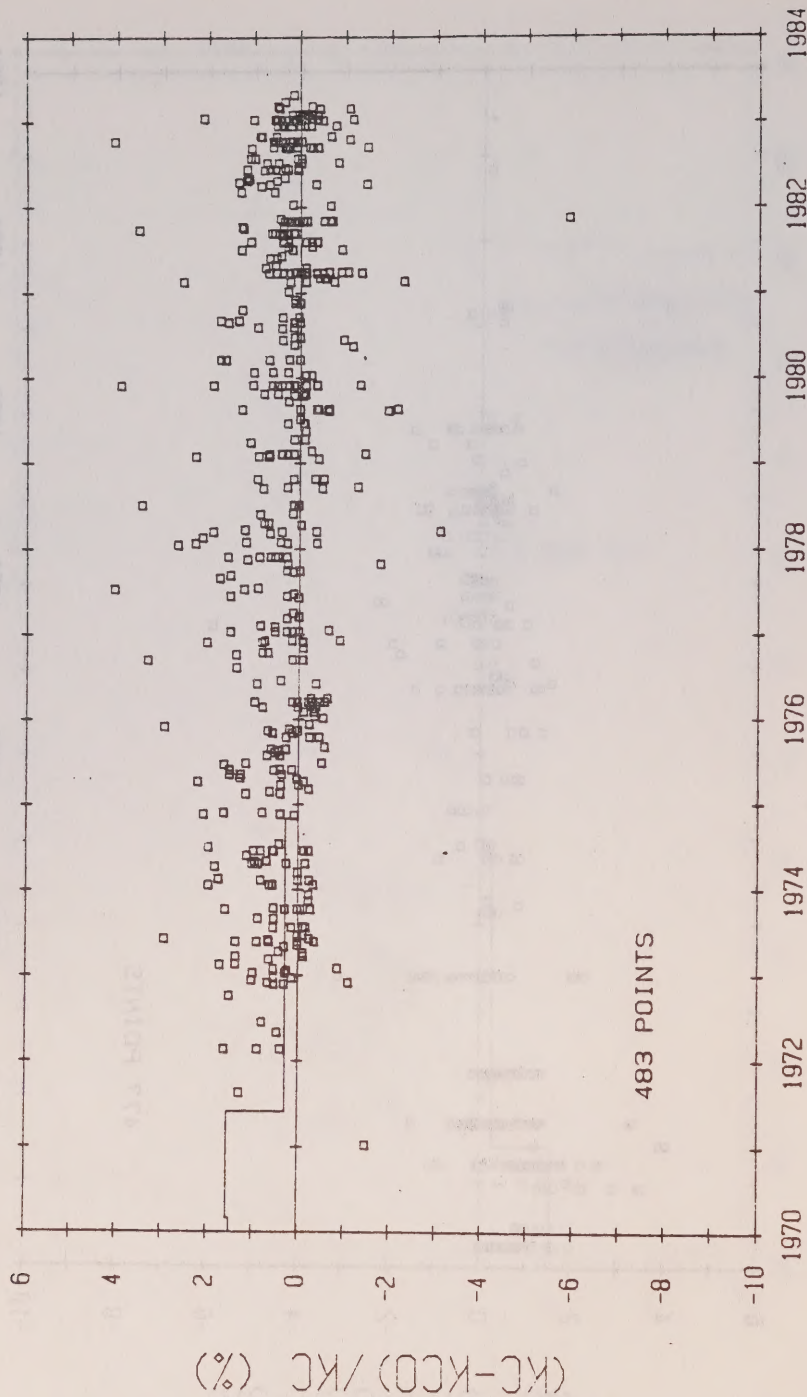
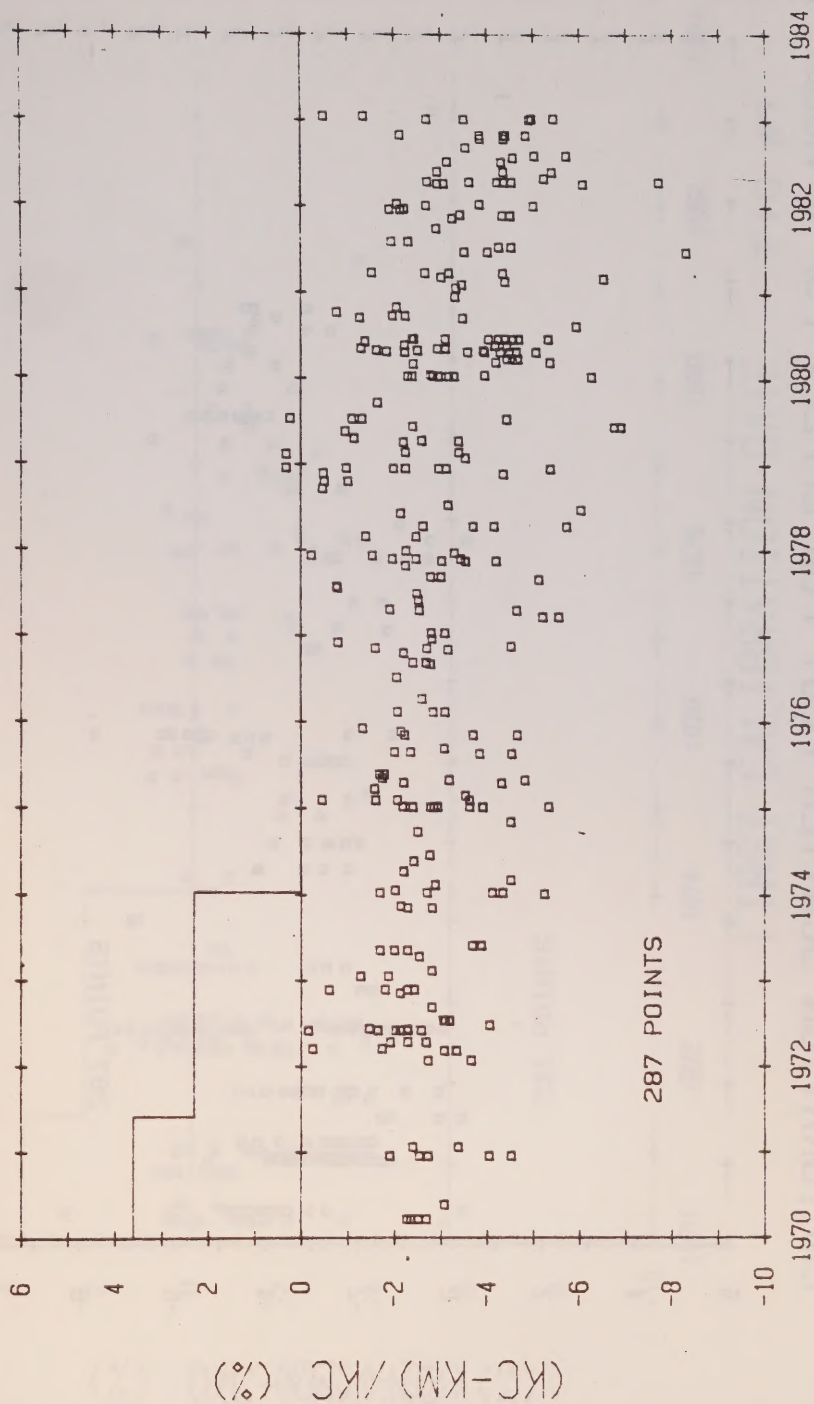


FIG #4

FIGURE 5.

CALIBRATION SCATTER PLOT FOR EPPELY PSP & MODEL 2



CALIBRATION DATE

FIG #5

FIGURE 6.

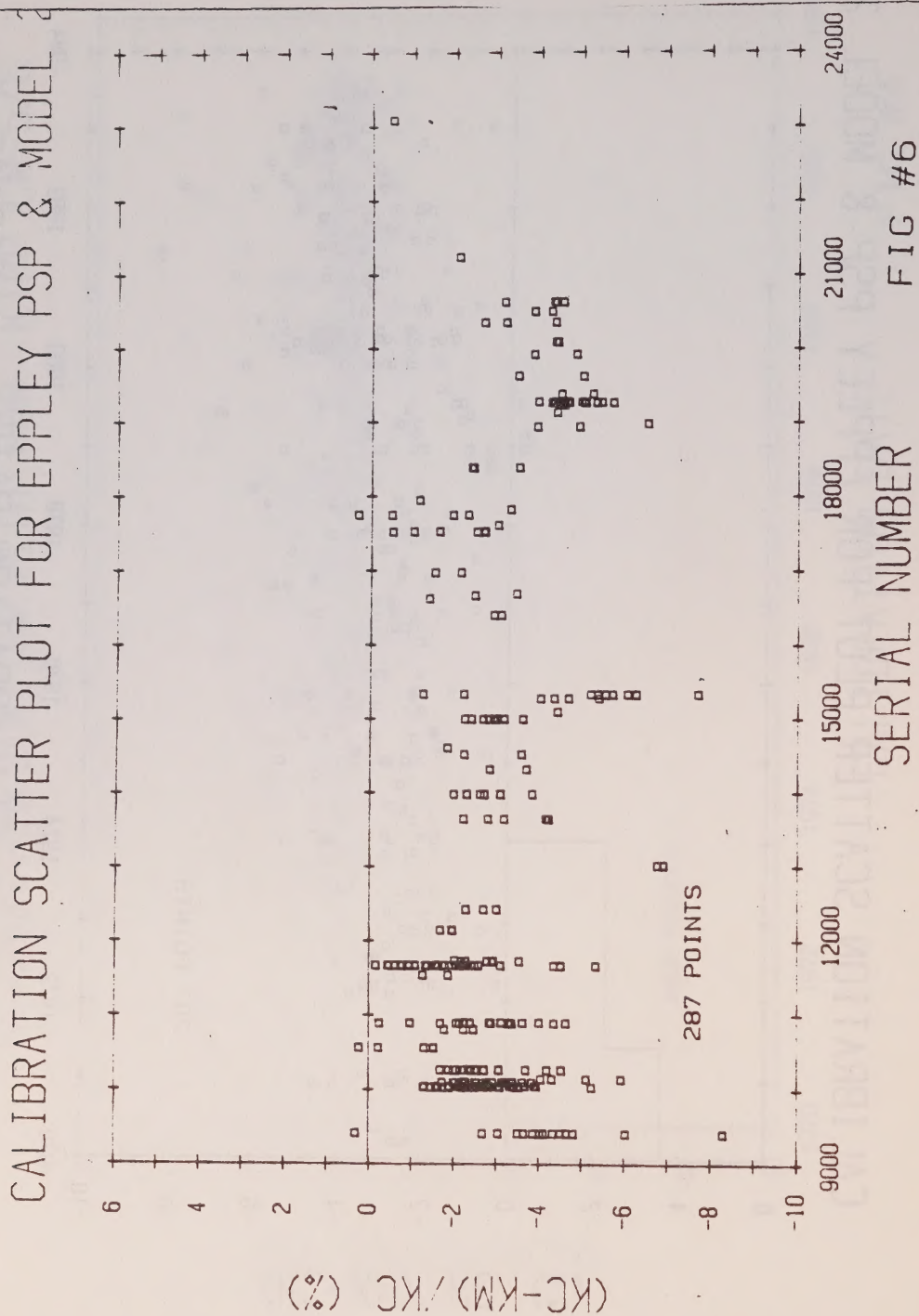
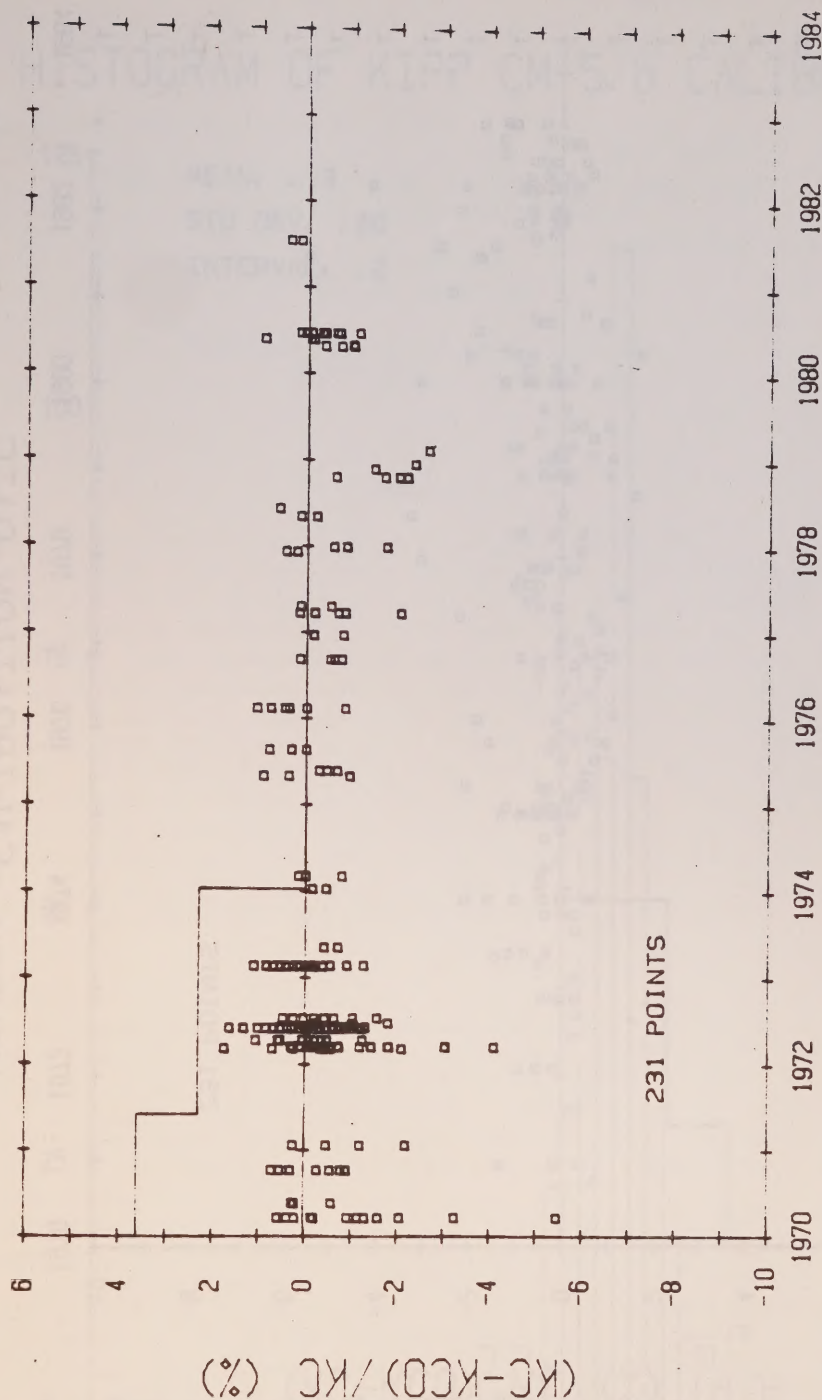


FIGURE 7.

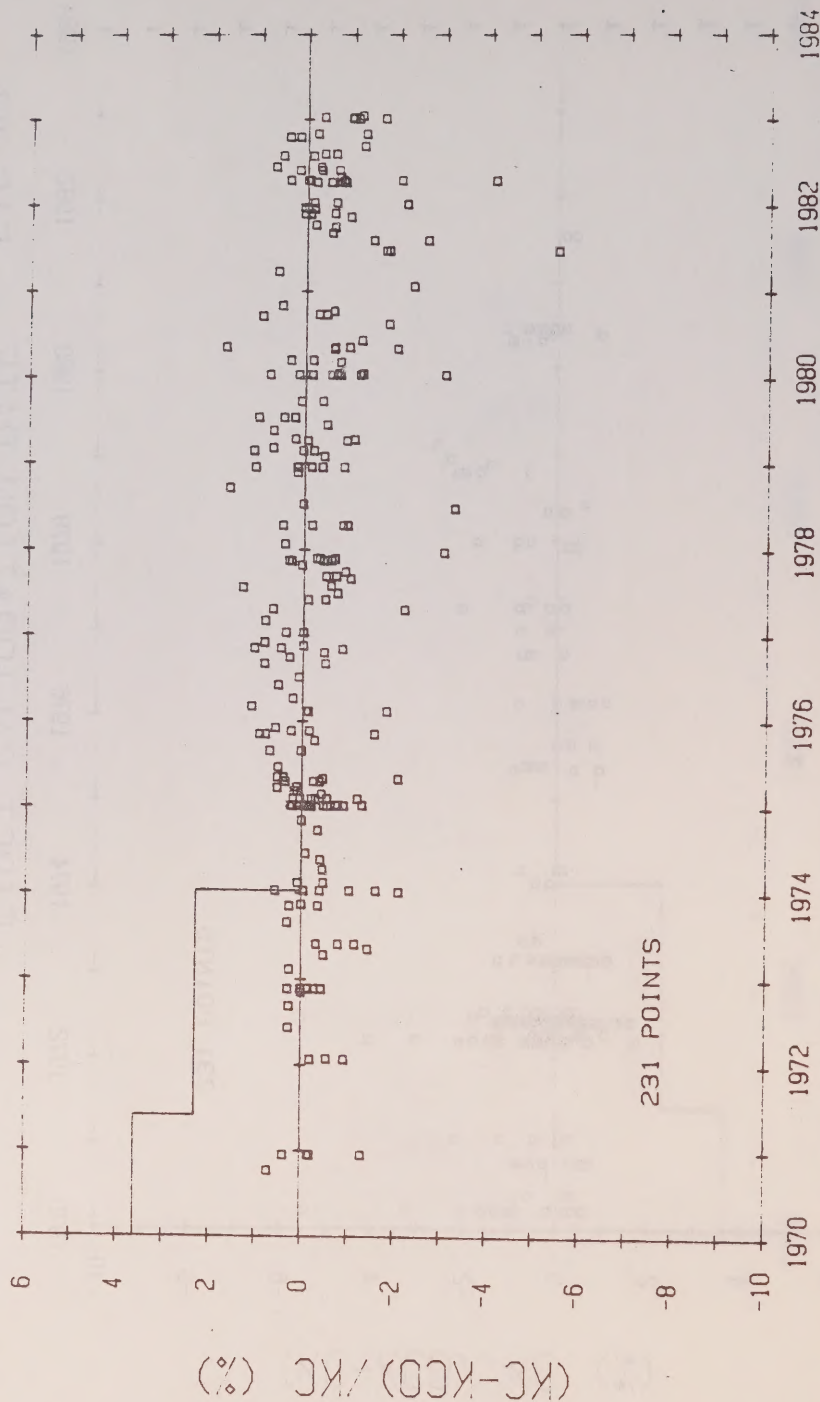
CALIBRATION SCATTER PLOT FOR EPPLEY PSP & MODEL 2



FIRST CALIBRATION DATE FIG #7

FIGURE 8.

CALIBRATION SCATTER PLOT FOR EPPLEY PSP & MODEL 2



CALIBRATION DATE

FIG #8

HISTOGRAM OF KIPP CM-5/6 CALIBRATIONS

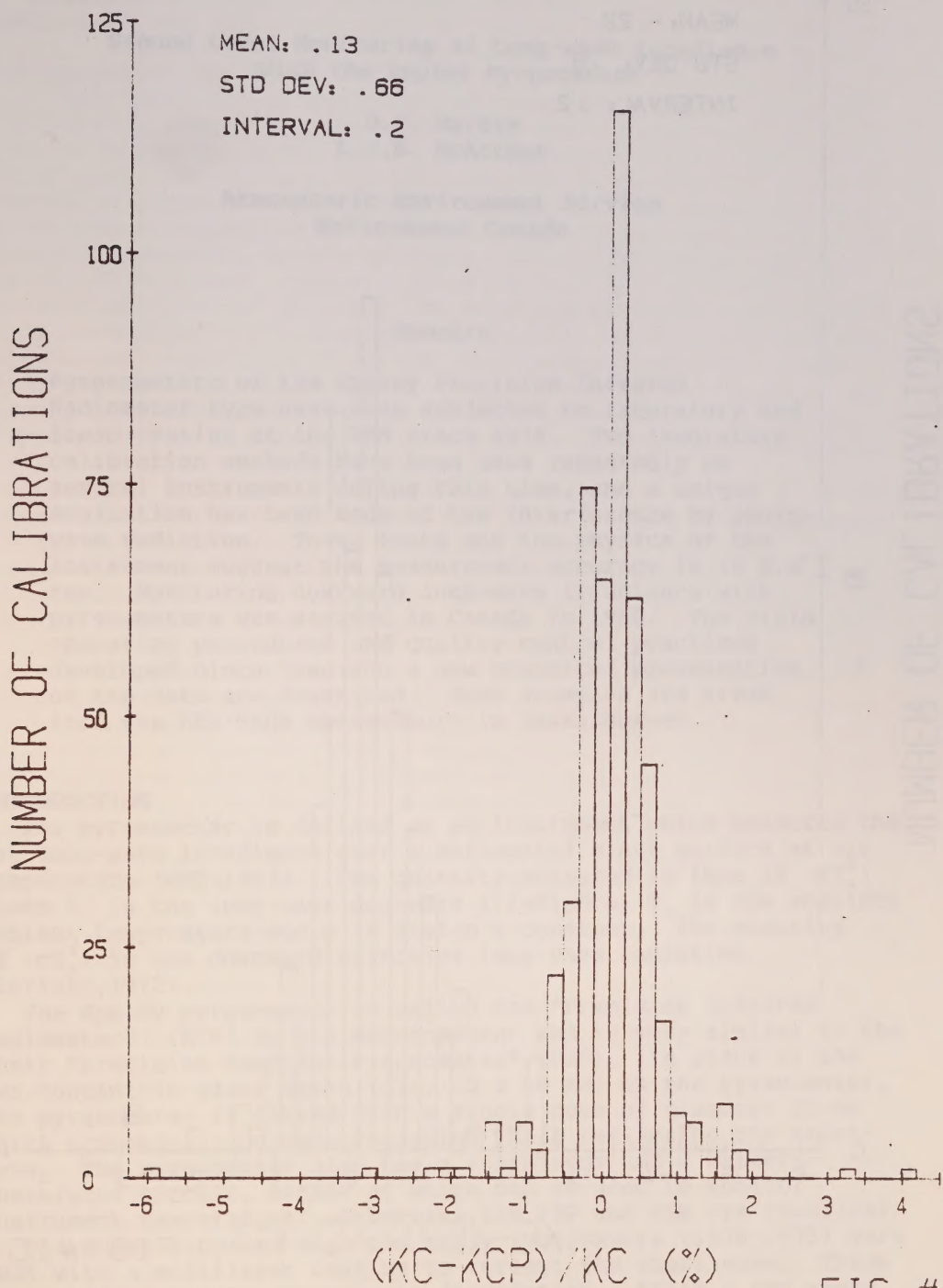
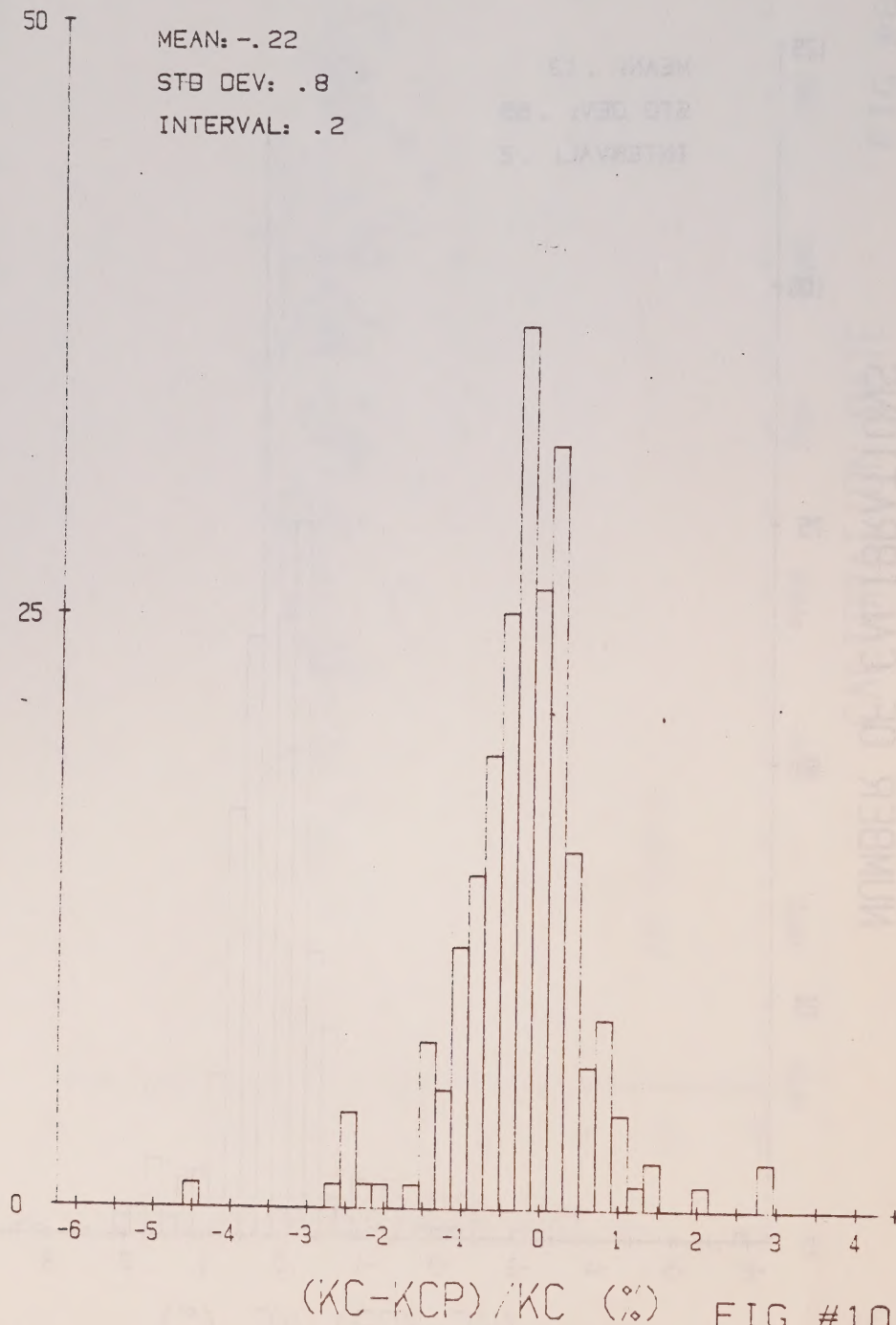


FIG #9

HISTOGRAM OF EPPLEY PSP/2 CALIBRATIONS

FIGURE 10.

NUMBER OF CALIBRATIONS



Ground Level Monitoring of Long-wave Irradiance with the Eppley Pyrgeometer

D.I. Wardle
L.J.B. McArthur

Atmospheric Environment Service
Environment Canada

Summary

Pyrgeometers of the Eppley Precision Infrared Radiometer type have been subjected to laboratory and field testing at the AES since 1978. Two laboratory calibration methods have been used repeatedly on several instruments during this time, and a unique evaluation has been made of the interference by short-wave radiation. These tests and the physics of the instrument suggest the measurement accuracy is 10 W.m^{-2} rms. Monitoring downward long-wave irradiance with pyrgeometers was started in Canada in 1980. The field operating procedures and quality control practices developed since then and a new graphical presentation of the data are described. Some examples are given from the AES RAGS observatory in Saskatchewan.

INTRODUCTION

The pyrgeometer is defined as an instrument which measures the net long-wave irradiance over a horizontal black surface at air temperature (WMO, 1983). The quantity measured is thus $(E^- - \sigma T_a^4)$ where E^- is the long-wave downward irradiance, T_a is the absolute ambient temperature and σ is Stefan's constant. The quantity $(E^- - \sigma T_a^4)$ is the downward effective long-wave radiation (Latimer, 1972).

The Eppley pyrgeometer is called the "Precision Infrared Radiometer" (PIR) by the manufacturer and is very similar to the their "Precision Spectral Pyranometer" (PSP). In place of the two concentric glass domes (dia. 30 & 50 mm) on the pyranometer, the pyrgeometer is fitted with a single dome of diameter 30 mm which transmits long-wave radiation while reflecting the short-wave. The pyrgeometer also has a thermistor and a battery-thermistor circuit, either of which can be used to monitor instrument temperature. Otherwise the PSP and PIR are identical.

The domes supplied with the early instruments (1970-1975) were KRS5 with a multilayer coating to reflect the short-wave. These domes suffered from atmospheric degradation. After a few weeks exposure the initially shiny outside surface acquired the look of

yellow ground glass, and the short-wave absorption increased. Silicon has been used instead of KRS5 since 1975 and these domes have proved extremely durable.

Both types of dome have a finite emittance and consequently, dome temperature influences the measurement. The dome may acquire a different temperature from the instrument by absorption of incident short-wave radiation, or by being subjected to very high air velocities as when mounted on an aircraft. Thus short-wave radiation and high speed ventilation both cause measurement errors, but by ventilating the dome and instrument together, at velocities where the kinetic heating is negligible, the error caused by short-wave absorption is reduced. Ventilation in this manner reduces the temperature differential between the dome and body by forcing both towards the ambient air temperature.

Use of the pyrgeometer in a low-speed ventilated housing is the main subject of this paper. The housing was developed at the Canadian National Atmospheric Radiation Centre (NARC) of the Atmospheric Environment Service (AES) for use with pyranometers.

PYRGEOMETER PHYSICS

The physics of the dome emission and pyrgeometer errors were formulated by Albrect, Poellot & Cox (1974). Their response function has since been used by several workers including Weiss (1981) and Foot (1986), but contains a simple error - a correct derivation is given here.

A simple model for the pyrgeometer is shown in Figure 1. A thermopile, which provides the instrument output voltage, senses the difference between the temperature of the black receiver surface T_s and of the instrument body T_b . When the receiver is in thermal equilibrium there is a balance between the power it receives on its exposed surface from radiation R_{net} and that transferred to it from the body by conduction, convection and radiation. Assuming that the transfer from the body and the generation of the thermopile voltage are both linear it follows:

$$R_{net} \propto (T_s - T_b) \propto \text{Voltage Output} \quad [1]$$

The relation between R_{net} and the incident downward irradiance E^- has to be determined. The upward and downward irradiances A^+ and A^- between the dome and the receiver must satisfy the relations:

$$A^+ = e_o \sigma T_s^4 + r_o A^- \quad [2]$$

$$A^- = e \sigma T_a^4 + r A^+ + t E^- \quad [3]$$

where e_o and r_o are the emittance and reflectance of the receiver, e and r are the emittance and reflectance of the dome seen from the inside and t is its transmittance. Solving for $R_{net} = A^- - A^+$ and using:

$e + r + t = 1$, and $e_o + r_o = 1$ gives:

$$\begin{aligned} R_{net}/(1-r_o)e_o t &= (E^- - \sigma T_a^4) + k (\sigma T_a^4 - \sigma T_s^4) \\ &= \text{Output} / \text{Responsivity} \end{aligned} \quad [4]$$

where $k = e / t$

With this response function there is no output when the pyranometer is in isothermal equilibrium with its surroundings as must be the case if the second law of thermodynamics is to be observed (i.e., if $T_s = T_a = T$ and if $E^- = \sigma T^4$, then Output = zero). The Albrect, Poellot & Cox function does not satisfy this condition except in the special case when $e_o = 1$. Their mistake originates in equation [3] of the 1974 paper where they ignore the reflectance of the receiver. They also introduced, and claimed to have measured, transmittances which depend on the direction of the energy flow. These differences are presumably artifacts of their measuring system.

The values of e and t in equation [4] should be close to those measured for normal incidence because all the radiation exchange between the dome and the receiver takes place within 19° of normal incidence at the dome. The 19° comes from the geometry of the 10mm diameter receiver inside the 30mm dome ($\arctan(1/3)$). However, Foot (1986) by experiment, and Berdahl & Fromberg (1982) by calculation, have shown that conduction of heat through the air from the dome to the receiver is several times the radiation term. Thus there should be a term proportional to $(T_a - T_s)$ representing conduction in equation [4]. Alternatively, conduction can be incorporated into the radiation term by choosing an empirical value for k considerably higher than the ratio e/t . Albrect, Cox & Prokofyev (1977) gave $k \sim 4.0$ (KRS5 dome) and Foot measured $k = 3.2 \pm 0.2$ which is in good agreement with Berdahl & Fromberg's value of $12 \text{ W.m}^{-2}.\text{K}^{-1}$ for the effect of dome temperature on the measurement. Because the dominant process is conduction and because conduction does not vary significantly with temperature, the linear formulation of Berdahl and Fromberg is preferable. If radiation were totally negligible, the value of k would vary as T^{-3} .

Transmission of solar radiation through the dome gives rise to a further term in equation [4]. Enz, Klink & Baker (1975) concluded from the transmission spectrum of the dome (KRS5 type) and a calculated atmospheric transmission, that there may be an effect of up to 7 Wm^{-2} . It is presumably influenced by water vapour absorption above $2.5 \mu\text{m}$. Direct transmission can be measured as the initial fast response (<10 seconds) to shading or unshading the instrument from sunlight. A shading experiment done in Toronto on just one day which was very cold and dry, indicated that the direct transmission was about 30 per cent of the total interference. Behrdahl & Fromberg measured $\sim 4 \text{ Wm}^{-2}$ by the same method.

Including the three interfering terms into equation 4 gives:

$$\frac{V}{K} = (E^- - \sigma T_s^4) + \frac{c}{t}(\sigma T_d^4 - \sigma T_s^4) + \frac{c}{t}(T_d - T_s) + \frac{t_g}{t} E_g^- \quad [5]$$

where:

- t_g is approximately the short-wave transmittance
(exact if $r_o = 0$)
- E_g^- is the short-wave downward irradiance
- K is the long-wave responsivity
- c is thermal conduction constant between the dome and receiver

MEASUREMENT OF SHORT-WAVE INTERFERENCE

The alternating sun/shade method, which is normally used to transfer calibration from a pyrliometer to a pyranometer, is also suitable for pyrgeometers. It is preferable to estimating the interference from simultaneous records of pyranometer and pyrgeometer readings on days with scattered cloud. Ryznar (1981) has explained that the influence of clouds on the long-wave radiation itself seriously limits the latter method.

In the NARC sun/shade procedure, the sun is shaded during alternate periods of 10 minutes by a 10cm diameter disc located 1.0 m away from the pyranometer. The outputs are recorded as one-minute integrals and data from the last four minutes of each 10 minute period are used in the calculation. A separate responsivity is first derived from each of the four unshaded measurements, and if the spread is less than $0.02 \mu V.W^{-1}m^2$, the mean value is archived. Otherwise the measurements for the whole cycle are discarded.

The sun/shade calibrations made throughout the year 1983 at Toronto on one pyrgeometer are shown in Figure 2. All seasons are represented in the data; there are 175 calibrations each the result of a 20 minute measurement cycle. For comparison, Fig.3 shows pyranometer results. The abscissa is the solar zenith distance and the ordinate is the short-wave responsivity - K_g . If there were no variation with zenith angle the pyranometer would satisfy the cosine law and would be an ideal pyranometer. It would respond uniquely to irradiance regardless of directional distribution of the incident radiation field.

Disregarding the six points below 0.05 in Figure 3 gives:

$$K_g = (0.125 \pm 0.025 \text{ rms}) \mu\text{V} \cdot \text{W}^{-1}\text{m}^2$$

The variation of K_g with zenith angle is less than 20 per cent. Consequently, taking linearity for granted, the response V_g to an arbitrary radiation field is properly represented by:

$$V_g = (0.125 \pm 0.025) \cdot E_g \quad \mu\text{V} \quad [6]$$

where E_g is the global (short-wave) irradiance.

These results were all obtained with the pyrgeometer mounted in the NARC ventilated housing. The interference on non-ventilated pyrgeometers is more variable and, when there is no wind, can be three times larger.

The NARC ventilator, which is used at all the AES radiation sites, is shown in Figure 4. A small electric cooling fan drives air from the base upwards and around the pyranometer body. At the top, the air is directed radially over the dome. The case is transparent polycarbonate with white paint on the inside except for a small window area left for viewing the bubble level. The outside diameter is 20 cm and the overall height about 16 centimetres. The power dissipation is 10 W, and the temperature rise inside the housing is about 1.5 Celsius.

CORRECTION FOR SHORT-WAVE INTERFERENCE

Correction of pyrgeometer readings can be based on monitoring the dome temperature following the method developed by Albrecht & Cox (1973) or, more obviously, on parameterization of the short-wave interference. The first approach has not been pursued at the NARC partly because of the additional complication of monitoring another variable and the difficulty of installing a thermistor or thermocouple to monitor the top of the dome without drastically changing the responsivity. However, the main reason for adopting the second method is the precision and simplicity of Equation 6 which parameterizes the sum of the three interfering terms in Equation 5. Using it for this purpose gives:

$$V = K (E^- - \sigma T_s^4) + K_g E_g^- \quad [7]$$

For this instrument (#11666), the long-wave reponsivity K is 4.75. The ratio, K_g/K is therefore 0.026 ± 0.005 and:

$$V/K = (E^- - \sigma T_s^4) + 0.026 E_g^- \quad [8]$$

in which the residual error is $0.005 E_g$, or $5 \text{ Wm}^{-2}\text{rms}$ maximum.

Four other pyrgeometers have had the short-wave responsivity measured at the NARC, though only at a small range of zenith angles. The ratio K_g/K is in the range 0.025 to 0.030 for all of them. It is therefore assumed that the value 0.026 is satisfactory for all, and Equation 8 is used for routine monitoring (Albrecht & Cox, 1975 derived 0.0311 for the KRS5 dome on an aircraft but the apparent agreement is coincidental).

PHYSICS OF VENTILLATION AND SHORT-WAVE INTERFERENCE

A speculative explanation can be offered of why the sum of all three interfering terms in Equation 5 can be expressed in the form of the transmission term under ventillated conditions.

Equation 5 shows that the conduction and radiation terms are both functions of the internal dome temperature T_a . Because the radiation term is approximately linear (see above) and the conduction term, which is larger, is linear, their sum is also linear in T_a . For a given direction of incident short-wave radiation, and for given steady air circulation around the outside of the dome, it is to be expected that T_a will be a linear function of the radiation.

The measurements represented by Equation 6 suggest that the NARC ventillator standardizes the thermal exchange between the air and the dome. Alternatively, the thermal exchange might always be kept strong enough to force the outside dome temperature very close to the air temperature, regardless of the ambient wind and the strength of the short-wave radiation, while the inside dome temperature is driven by the absorption of radiation. Some support for the second possibility comes from Enz *et al.* (1975) who observed that the short-wave interference cannot be reduced indefinitely by increasing ventillation speed. This is consistent with the fact that some short-wave energy is deposited in the dome material and at its inner surface and also with the hypothesis that the ventillation keeps the outside dome surface at air temperature. However, the high thermal conductivity of silicon ($164 \text{ W.m}^{-1}.\text{K}^{-1}$) negates any possibility of significantly different temperatures across the dome thickness.

There remains the question of why the net effect has the cosine dependance on incidence angle. It is possible that the conduction and radiation come mainly from the top of the dome, which being horizontal, absorbs short-wave energy according to the cosine of the zenith angle.

SIMILARITIES TO THE EPPLEY PSP.

The pyrgeometer and the pyranometer share the same thermopile and body and have the same internal dome size. The thermal impedance between the receiver and the body are the same and if convection does not occur within the PSP dome, it will also be absent from the pyrgeometer.

The temperature rise of the PSP receiver is about 4 C for an irradiance of 1000 W.m^{-2} . The long-wave transmittance of the pyrgeometer dome is about 0.4 so that with a maximum long-wave signal of 200 W.m^{-2} the temperature rise/fall is only 0.32 Celsius.

Non-linearity and the effect of tilting on the responsivity of the PSP have been shown to be negligible by Dehne (1981). In this regard, the PSP is better than most other pyranometers, probably because of the small temperature gradients and the absence of convective circulation in the dome cavity. Because the temperature differences are even smaller in the pyrgeometer, there is no reason to suspect non-linearity or changes in responsivity from tilting or inverting the instrument or by reversing the direction of the effective radiation.

CALIBRATION PROCEDURES

During the period 1980-1986, 29 of the silicon dome pyrgeometers have been calibrated by routine NARC methods a total of 138 times. Many of these calibrations are the mean of several individual determinations. Three different methods have been used.

The fixed point NARC Black Body method uses the apparatus shown in Figure 5. The lower compartment is approximately 30 x 30 x 60 centimetres. Water at 25 C is circulated through its hollow brass walls. There is an aperture of 12.5 cm diameter in the top and just above this is a shutter, also of hollow brass with the same water flowing through it. The cone above is 70 cm high and has a base diameter of 20 centimetres. Oil at 70 C is pumped around the outside surface of the cone. During a calibration, the pyrgeometer is placed directly below the aperture. It is left for 30 minutes to equilibrate; the zero output is then measured, the aperture is opened and the signal is measured after 90 seconds. A second cycle of zero and full signal measurements is taken 10 minutes later. The result is calculated from the difference signal, Stefan's constant and the geometry of the opening.

The second, the Sphere Cooling method, uses the NARC integrating sphere whose primary purpose is calibration of pyranometers. The sphere diameter is 1.9 m and its walls are 3 mm thick steel. Being so large compared with a pyrgeometer, it makes an effective black-body enclosure. For a calibration, the pyrgeometer is first put in a small thermostatically controlled oven and brought to some temperature between 35 C and 55 Celsius. It is then placed in the sphere and the pyrgeometer signal and temperature are recorded for 180 minutes. The sphere temperature is also recorded by means of a thermistor suspended in the middle of the sphere; it may change by up to 0.5 C during the calibration. The result is obtained by plotting the signal against the quantity $(\sigma T_s^4 - \sigma T_p^4)$ where T_p is the sphere temperature. The gradient obtained gives the responsivity.

The third method used is that described by Eppley (1971) using the 75 mm diameter black cup supplied by Eppley as a reference. In general, this has only been done once for each pyrgeometer because the results at the NARC have invariably been much higher than the manufacturer's values and those obtained by the other two methods.

From an examination of the long-term calibration results the following can be noted:

1. The sphere cooling method gives the more stable results. In 9 of the 13 instruments calibrated more than once and separated by three years or more, the overall range is less than 3 per cent.
2. The manufacturer's calibration is quite close to that obtained using the sphere cooling method (15 of the 18 comparisons are closer than 3 per cent; 11 of 18 are closer than 2 per cent and the mean difference is not significant).
3. The NARC Black Body method gives slightly higher responsivities and there is more scatter from year to year than with the cooling method. The relation between the two methods is:

$$\text{NARCB} - \text{COOLING} = 2.5 \pm 3.5\% \text{ (rms)}$$

4. The Eppley black cup gives values typically 10 per cent higher than those obtained by the other three methods.

PRECISION AND ACCURACY OF THE NARC METHODS.

In the Sphere Cooling method, the least squares linear fit analysis usually gives better than 0.5 per cent rms for the responsivity precision. When the first three minutes of data are ignored, the precision improves to 0.2 per cent. Calibrations made on successive days show a repeatability of about 1.0 per cent rms. The starting temperature and the cooling rate can affect the result. Changing the starting temperature from 35 C to 50 C increases the result by about 1 per cent. Reducing the cooling rate to half of its normal value by wrapping the pyrgeometer body in fibreglass insulation decreases the result by less than 1 per cent. Increasing the cooling rate by a factor of three, by putting the pyrgeometer in a NARC ventilator, causes a 10 per cent increase in the result.

The NARC black body method also has a day-to-day repeatability of about 1 per cent rms. The temperature distribution in the cone and in the lower chamber are each uniform within <0.2 C which translates to an uncertainty of <0.5 per cent in the black body radiation. A measurement error of 1 per cent in the output voltage of typically 150 μV is the most probable cause of the variability in the result.

The long-term precision, derived from the calibration records, is 2 per cent rms for the Cooling Method and 3 per cent for the NARCB method, each of which is significantly higher than the 1 per cent day-to-day variability. With the Cooling Method, the increase is explained by apparently random changes in the procedure, e.g., the influence of starting temperature. There is no adequate explanation of the 3 per cent rms long-term precision of the NARCB method.

It is hoped to improve the consistency of the Cooling Method in future by always starting at 45 C. The NARCB method will be investigated further by means of a second black body enclosure offering greater flexibility to change the geometry and temperatures.

The NARCB calibration is preferred for field use because the conditions under which the calibration is made are much closer to field conditions than is the case when the Cooling Method is used. In the NARCB method, the radiation originates from within 35° of the zenith and the surrounding air temperature is close to that of the pyrgeometer. By contrast, with the Cooling Method, the radiation is isotropic and the air temperature equals that of the radiation temperature.

The accuracy of using the NARCB result in the field is estimated at 4 per cent rms if spectral effects are neglected. The 2.5 per cent mean difference between the NARCB and cooling methods is taken as a measure of the variation of responsivity over the range of conditions in which the instrument is used and calibrated. It is probably a safe upper limit, because field conditions seldom approach those encountered with the Cooling Method. Combining the 2.5 per cent variation estimate with the 3 per cent calibration precision (according to the square law) yields the 4 per cent accuracy. Spectral effects are considered below.

Results from the Eppley black cup and from the Cooling Method with the pyrgeometer installed in a ventilator have been disregarded in the above discussion on accuracy. As mentioned, they are 10 per cent higher than those from the other methods because of excessive dome heating, either by air conduction from the cup surface, or by forced ventilation with hot air. These conditions are not encountered in ground-level monitoring.

SPECTRAL CONSIDERATIONS.

A typical atmospheric spectrum simulated by the Lowtran 6 program, and a black body spectrum at ambient air temperature, are shown in Figure 6. The pyrgeometer, provided it is at ambient temperature, measures the difference between these two spectra. Thus the driving radiation for the pyrgeometer comes from the two atmospheric windows which extend over the wavelength ranges of 8-13 μm and 16-22 micrometres.

More water vapour in the atmosphere first eliminates the 16-22 μm window and partially fills the 8-13 μm window. High clouds fill both windows partially and low cloud or mist can close both. The feature at 9.5 μm is caused by ozone. Some other calculated spectra are shown in Figure 7.

If the pyrgeometer is not at the air temperature, it is also driven by radiation with a differential black body spectrum of magnitude ($\sigma T_a^4 - \sigma T_g^4$). The differential spectrum at 300 K is shown in Figure 8. It is similar to the black body spectrum for 450 K.

The 300 K differential spectrum of Figure 8 is also very close to the active spectrum for both of the laboratory calibrations.

The spectral response of the pyrgeometer is largely determined by the transmission of the silicon dome, one example of which is given in Figure 9. Comparing several such measurements on different domes has revealed some differences in the transmission at wavelengths below 4 μm , but very little above 4 micrometres. It should be noted that the two sharp absorption features at 9 μm and 16.5 μm are both within the atmospheric windows.

A careful numerical study of these spectra and their products would be appropriate but has not yet been done at the NARC. Foot has made a start on this work, but he may have used spectra of the simple downward irradiance rather than those of the effective radiation. What follows here are some preliminary subjective estimates derived from inspection of the relevant spectra.

The mean response to the 300 K differential spectrum appears to be within 3 per cent of the mean 8-13 μm window. The 16-22 μm response is about 10 per cent lower than the 8-13 μm response. The response in the 8-10 μm region is about 10 per cent higher than in the 10-13 μm region. Consequently, provided spectra from high altitudes are excluded, it appears to the writers that the uncertainties in measurement caused by the dome transmission are likely to be in the range 3-6 per cent.

OPERATIONAL MONITORING AND QUALITY CONTROL

Pyrgeometers have been in continuous operation since 1980 at Woodbrige near Toronto and in Vancouver at a site run by John E. Hay. In 1986 monitoring was started at a special site chosen for long-term study of radiation and the Radiatively Active Gases (RAGS) at Asquith, Saskatchewan. The methods used reflect experience gained at the other locations.

The pyrgeometer and pyranometer are mounted in NARC ventilators, which keeps them free of condensation, ice and snow, and which helps to keep them clean. They are inspected and cleaned daily. The battery circuit in the pyrgeometer has caused many problems for the staff at the NARC and at other institutions. The pyrgeometer temperature is therefore monitored by the resistance of the thermistor.

The data system records the sensor resistance as well as the voltages and the thermistor resistances for the air and pyrgeometer temperatures. Readings are taken every 15 seconds and 2 minute mean values are stored.

It is a point of faith in the AES that the quality control of radiation data must include inspection of daily records by a technician. This conviction has been reinforced by several futile attempts at complete automation. The daily graphical presentation is shown in Figure 10, it has a linear scale in downward irradiance and a matching non-linear scale in equivalent radiation temperature. The air temperature is plotted on the same graph. The difference between the two curves is the effective radiation ($L - \sigma T_a^4$), which is nearly always negative.

The instrument serial number, responsivity and measured resistance are all printed on the graph. This verifies that the correct instrument was in place. The hourly totals are also shown. In the routine quality control, these are transferred to a separate data bank after the graph has been inspected.

Figure 11 shows the global radiation on the same day. There was a clear morning, scattered cloud in the afternoon followed by a thunderstorm and finally a partially clear evening.

The fluctuation in the records is generally least during the night - typically 3 Wm^{-2} and 6 Wm^{-2} during the day. This behavior can be seen in the first part of Figure 11. It is assumed that this is random instrument noise caused by small fluctuations in the air temperature.

INVENTORY OF ERRORS

Table 1 is a reasonably comprehensive list of the errors that contribute to a pyrgeometer measurement at the ground. It includes suggestions on how each type could be reduced.

A modification to the instrument to reduce the dome conduction effect, possibly by evacuating the instrument or by using the method developed by Foot with his MRF pyrgeometer, would improve the accuracy. The spectral properties of the dome would be better in the $8\text{--}22 \mu\text{m}$ band if it were half as thick. Unfortunately, this would make it fragile.

The result of combining the above errors clearly depends on what kind of measurement is being considered. For example, it depends on the integration time and on the strength of solar radiation, but the resultant must typically be in the region of 10 Wm^{-2} rms. The expression:

$$(\text{rms error})^2 = (7 \text{ Wm}^{-2})^2 + (5\%)^2$$

is obtained by formally combining all the above errors taking the larger value where there is a choice.

TABLE 1.

Error Type	Magnitude RMS	Remarks and Possible Reduction Strategy
A. temperature	2 Wm^{-2} 1 Wm^{-2}	0.2 C accuracy 0.1 C precision for T_s & T_a is smaller than most other errors.
B. instrument noise	3 Wm^{-2} / 6 Wm^{-2}	Night/day. caused by ambient temperature fluctuations. The quoted figures refer to 2 minute averages. Can be reduced by longer averaging.
C. calibration	4%	A laboratory apparatus which allowed independent control of the long-wave radiation, and ambient temperature and velocity would help clarify the physics and improve the calibration accuracy.
D. spectral	1% to 2.5%	i.e. range of 3 to 6%. Can be reduced by using calculated spectra if rough estimates of water vapour and cloud height are known.
E. residual after correction for short-wave	5 Wm^{-2}	i.e. $0.005L_g$ could be reduced by operating with a tracking shade disc & correcting for diffuse short-wave radiation.

CONCLUSIONS

The stability of the Eppley silicon dome pyrgometers, which have been used and repeatedly calibrated over a period of several years, is better than 3 per cent.

Short-wave interference has been measured by the shading disc technique over a range of zenith angles many times throughout a year at Toronto. The pyrgometer was in a NARC ventilated housing. The derived correction is 2.6 per cent of the global radiation with a residual of 0.5 per cent rms.

With the short-wave correction applied, and with the instrument in the NARC housing, the typical overall accuracy is 10 W.m^{-2} rms. This compares favourably with short-wave measurements by pyranometers and is much better than that achieved by pyrrometers. The following practices could significantly improve the accuracy:

1. Continuous use of a shade disc with correction for diffuse short-wave radiation.
2. Calculation of spectral corrections based on meteorological parameters.
3. Tighter standardization of calibration methods and further laboratory characterization.

REFERENCES

- Albrecht, B. & Cox, S.K. (1977). Procedures for improving pyrgometer performance. J. Appl. Meteor., 16: 188-197.
- Albrecht, B., Cox, S.K. & Prokofyev, M. (1977). An analysis of GATE aircraft radiation measurements. Bull. of Am. Met. Soc., 58: 950-955.
- Albrecht, B., Poellot, M. & Cox, S.K. (1974). Pyrgometer measurements from aircraft. Rev. Sci. Instrum., 45: 33-38.
- Berdahl, P. & Fromberg, R. (1982). The thermal radiance of clear skies. Solar Energy, 29: 299-314.
- Dehne, K. (1981). Dependency on tilt angle of pyranometer sensitivity. Proceedings fo the CIE Symposium on Light and Radiation Measurement, May 1981. Budapest: Hungarian National Committee of the CIE.
- Enz, J.W., Klink, J.C. & Baker, D.G. (1975). Solar radiation effects on pyrgometer performance. J.Appl.Meteor., 14:1297-1302.
- Eppley Laboratory Inc. (1971). Instrumentation for the Measurement of the Components of Solar Radiation.

Foot, J.S. (1985). A new pyrgometer. J. Atmos. and Oc. Tech. 3: 363-370.

Latimer, J.R. (1972). Radiation measurement. International Field Year for the Great Lakes - Technical Manual No. 2. [available from the Atmospheric Environment Service, 4905 Dufferin St., Downsview, Ont., M3H 5T4, Canada.].

Ryznar, E. & Weber, M.R. (1982). Comments "On the performance of pyrgometers with silicon domes." J. Appl. Meteor., 21: 1208-1210.

Weiss, A. (1981). On the performance of pyrgometers with silicon domes. J. Appl. Meteor., 20: 962-965.

World Meteorological Organisation. (1983). Guide to Meteorological Instruments and Methods of Observation. WMO-No.8: Geneva, Switzerland.

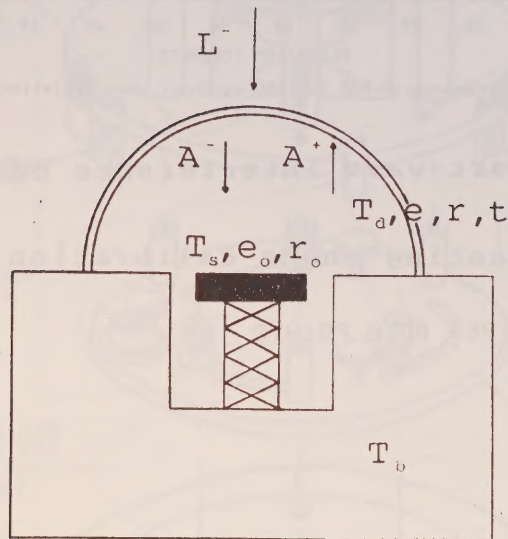


Figure 1.
A Model Pyrgometer

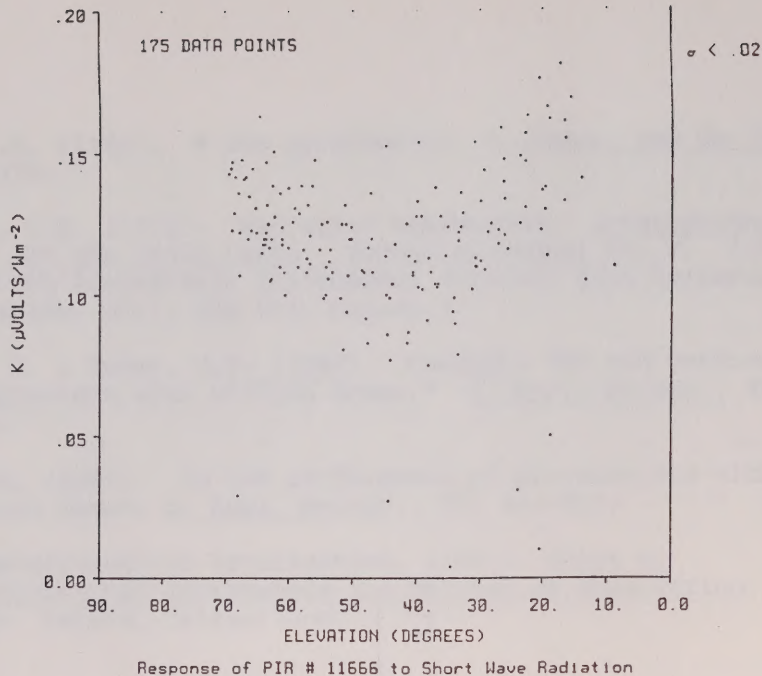
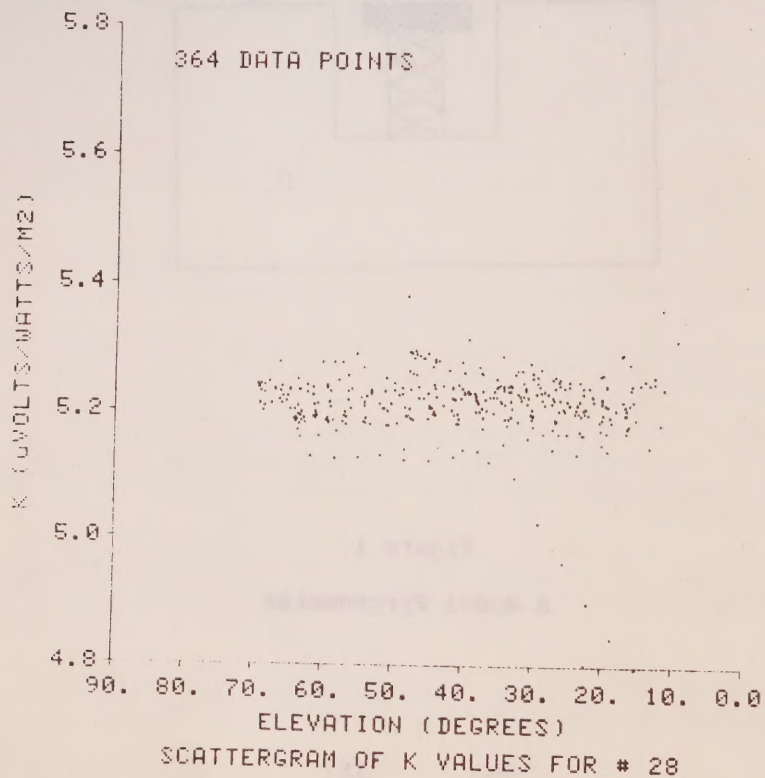


Figure 2. Short-wave interference on a pyrgeometer.

Figure 3. Alternating shade calibration of a pyranometer.



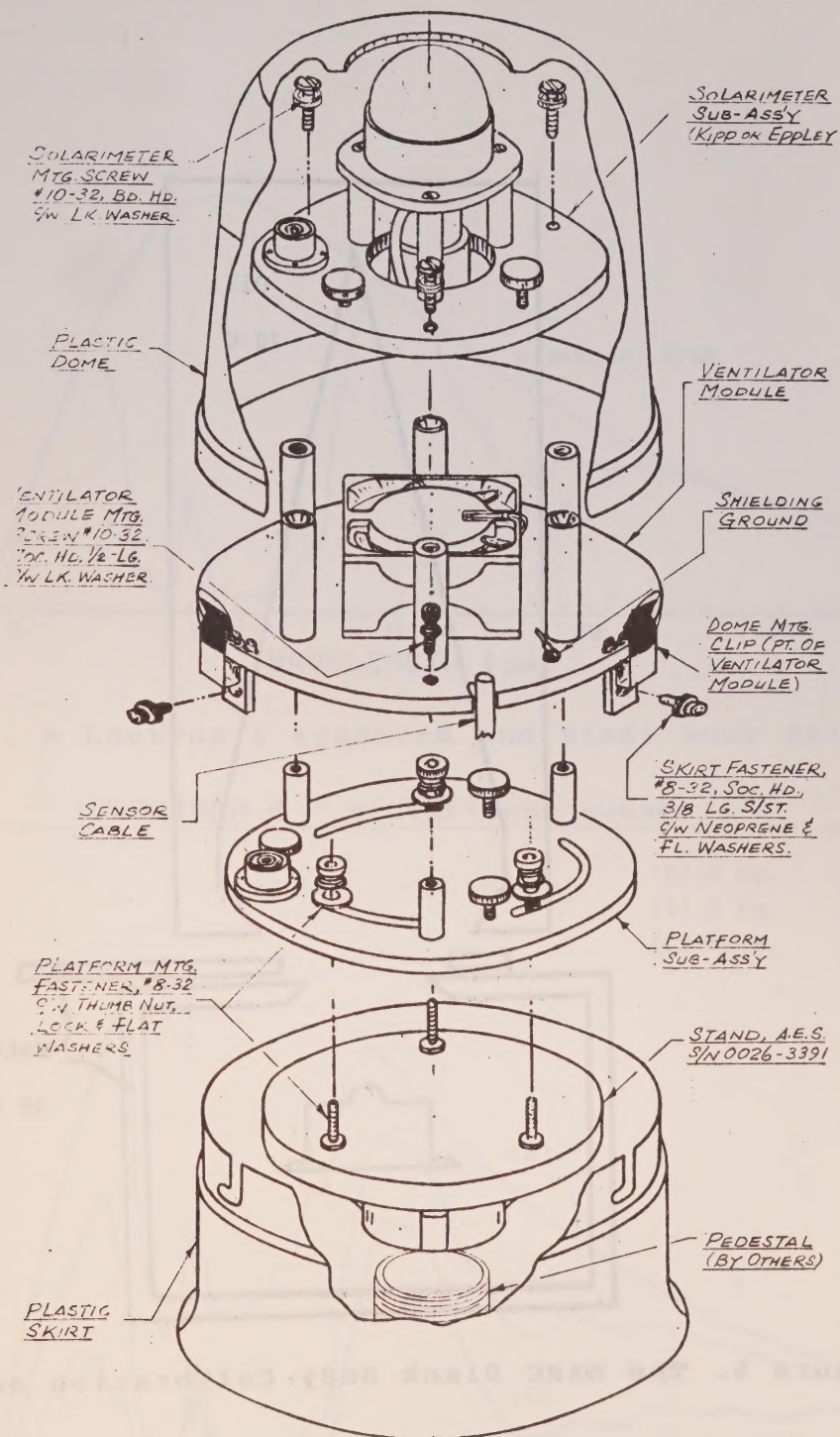


Figure 4. The NARC ventillator (with a CM-5).

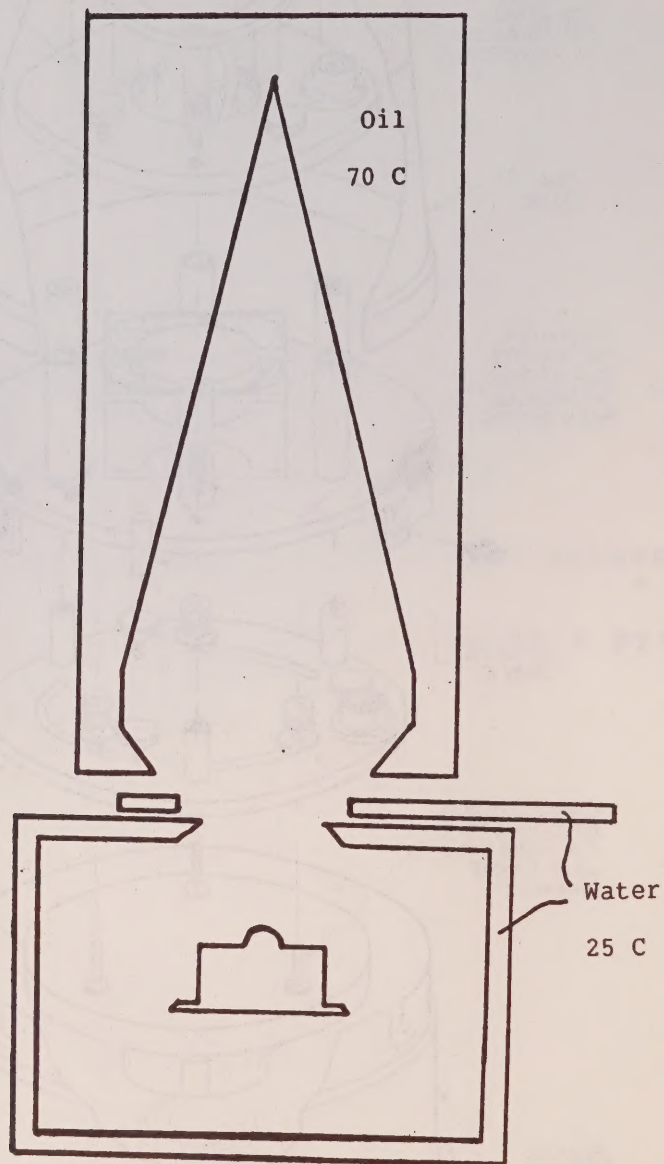


Figure 5. The NARC Black Body Calibration enclosure.

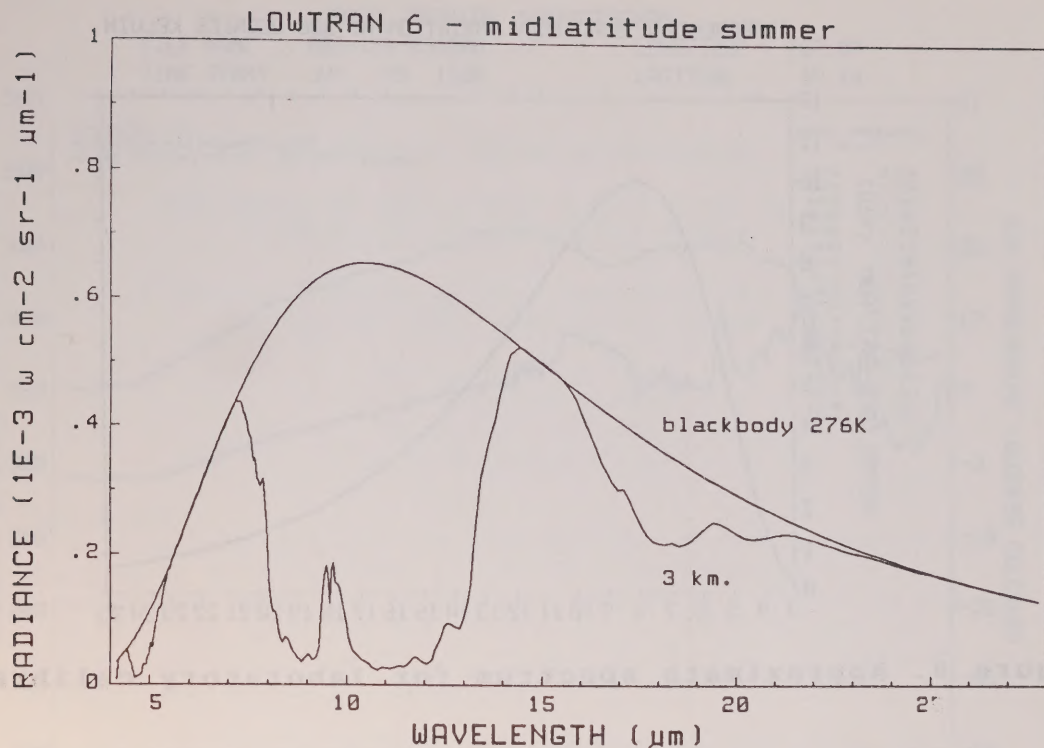


Figure 6. A Lowtran 6 spectrum and black body emission.

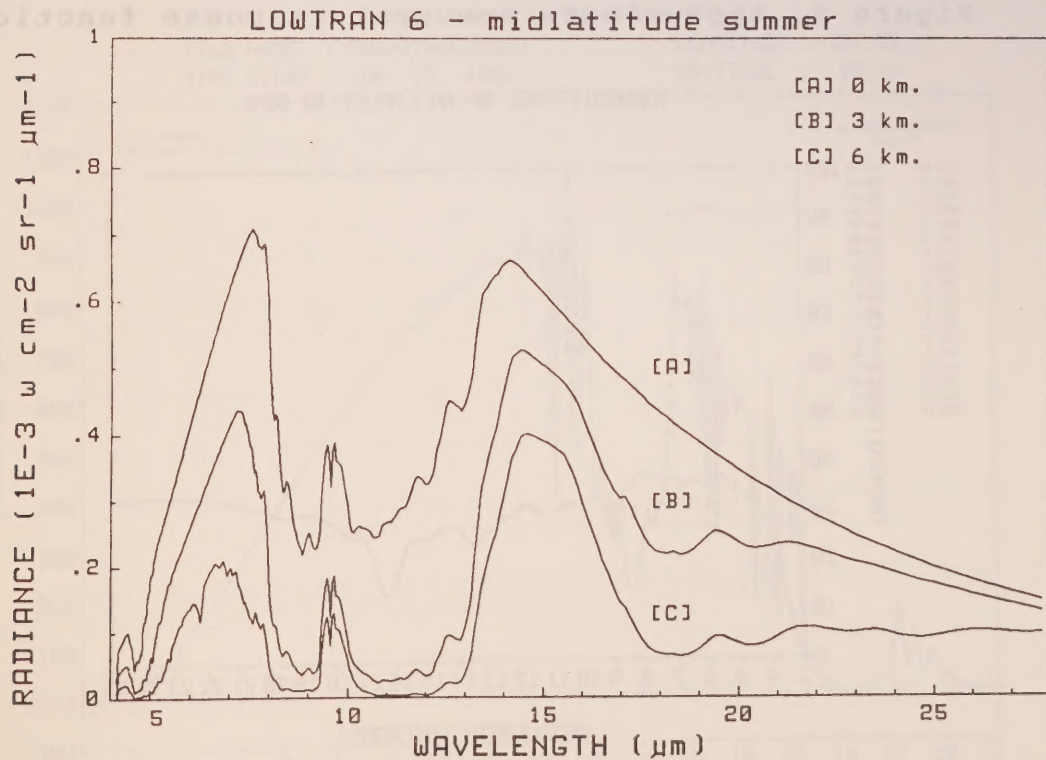


Figure 7. Midlatitude summer spectra at three altitudes

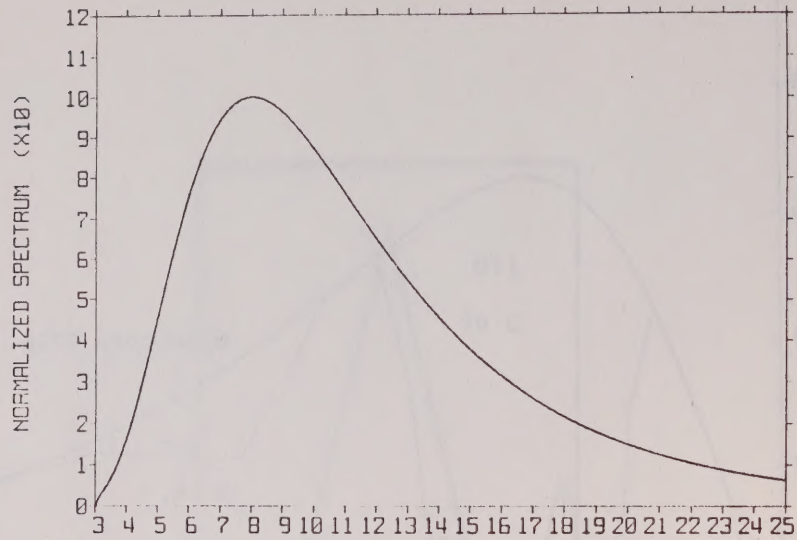
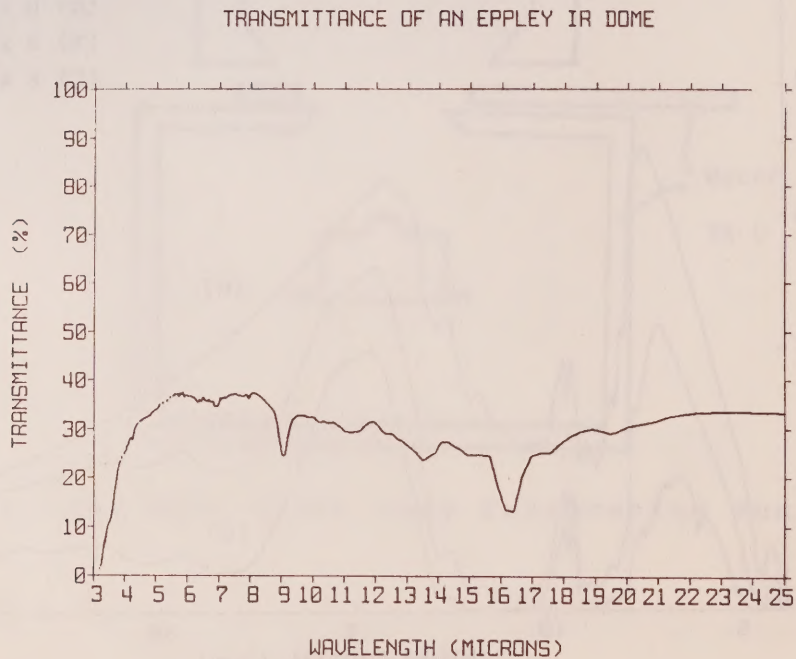


Figure 8. Approximate spectrum for laboratory calibration.

Figure 9. Approximate spectral response function.



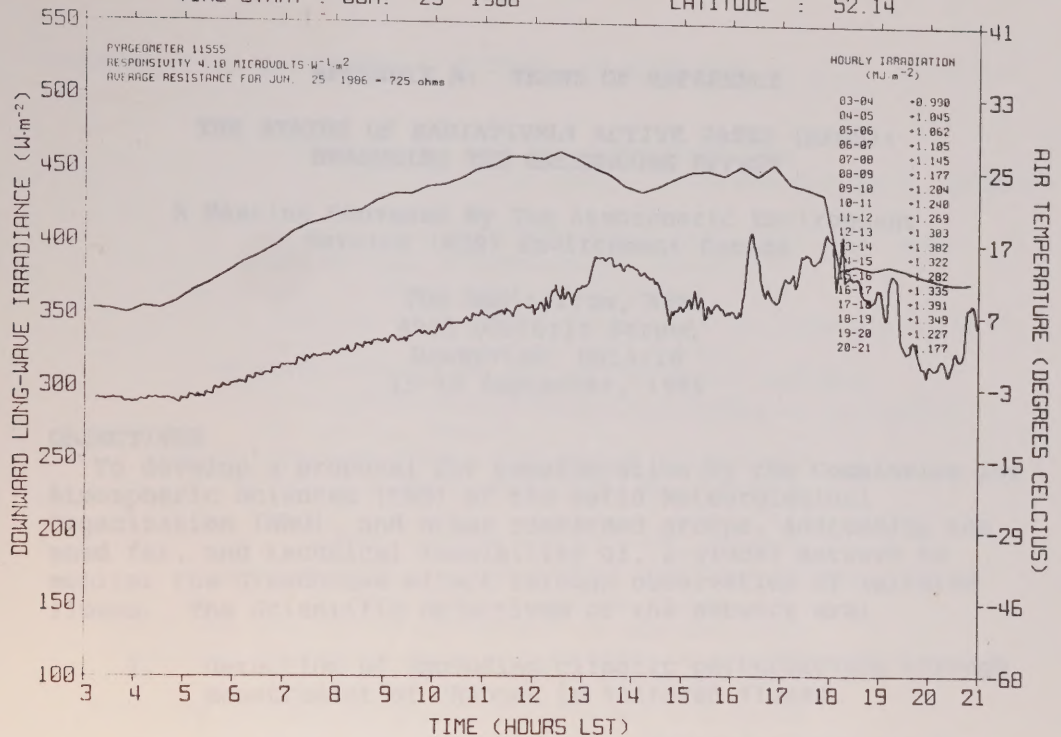
RAGS, ASQUITH, SASKATCHEWAN

FILE NAME : R86-176-030000

LONGITUDE : 107.07

TIME START : JUN. 25 1986

LATITUDE : 52.14



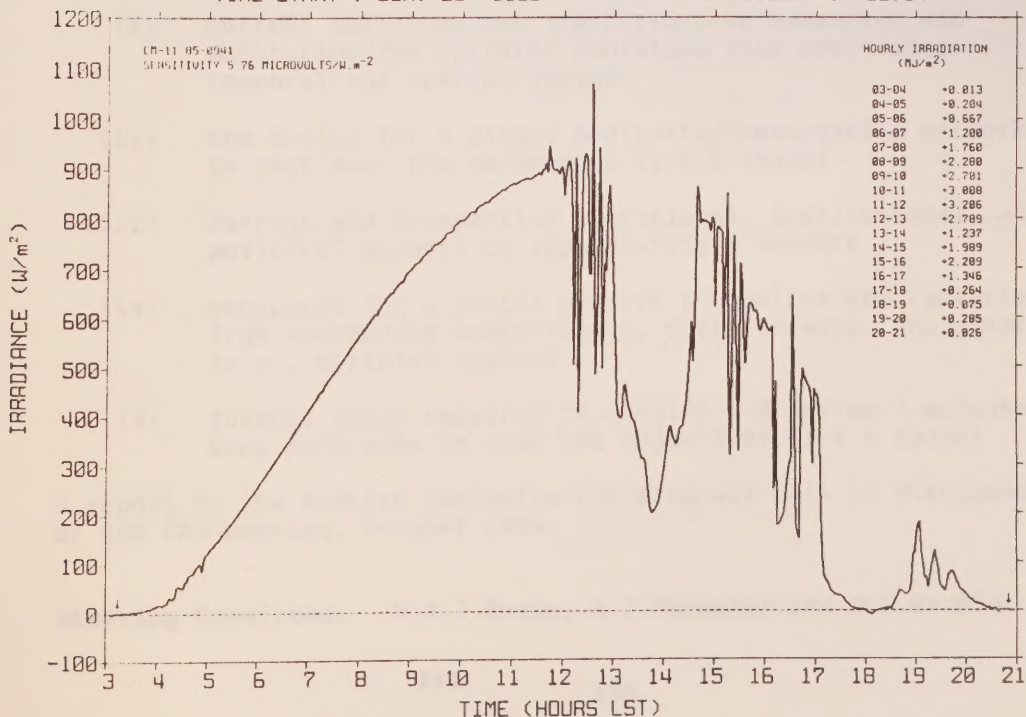
RAGS, ASQUITH, SASKATCHEWAN

FILE NAME : R86-176-030000

LONGITUDE : 107.07

TIME START : JUN. 25 1986

LATITUDE : 52.14



Figures 10 and 11. Downward short- and long-wave irradiances measured throughout a day.



Figure 1. Temperature vs. Time.

Figure 1 shows the temperature of the system as a function of time. The temperature starts at 100°C and decreases to 50°C over 10 minutes. The second series starts at 50°C and increases to 80°C over 10 minutes.



APPENDIX A: TERMS OF REFERENCE

THE STATUS OF RADIATIVELY ACTIVE GASES (RAGS): MEASURING THE GREENHOUSE EFFECT

A Meeting Convened By The Atmospheric Environment
Service (AES) Environment Canada

The Auditorium, AES
4905 Dufferin Street
Downsview, Ontario
15-19 September, 1986

OBJECTIVES

To develop a proposal for consideration by the Commission for Atmospheric Sciences (CAS) of the World Meteorological Organization (WMO), and other concerned groups, addressing the need for, and technical feasibility of, a global network to monitor the Greenhouse effect through observation of infrared fluxes. The Scientific objectives of the network are:

1. detection of impending climatic perturbations through measurement of changes in infrared fluxes
2. provision of a database for validation of radiation models

It is intended that the proposal should cover the following:

- (i) current abilities and limitations in measuring and monitoring the infrared radiation flux over large temporal and spatial scales
- (ii) the design for a global monitoring/observation network to best meet the objectives (1 & 2 above)
- (iii) current and prospective operational, institutional, and political aspects of implementing a network
- (iv) prospects for a global network to monitor the radiation from Greenhouse constituents, their effects, and other (e.g., visible) spectra
- (v) further steps required to develop and refine a measurement programme to meet the objectives (1 & 2 above)

A report on the meeting including the proposal will be discussed at the CAS meeting, October 1986.

Steering Committee: W.F.J.Evans, A.J.Forester and D.I.Wardle

APPENDIX B: MEETING AGENDA

Monday, 15th September

INTRODUCTION

Welcome, Arrangements, Agenda
A. Forester (Dartside)

GENERAL OVERVIEWS OF THE GREENHOUSE PROBLEM

Chairman, P. Merilees (AES)

Chairman's Appraisal: RAGS and the Climate
Problem. P. Merilees (AES)

General Circulation Models (GCMs)
G. Boer (AES)

Calculations on Greenhouse Radiation and Their
Empirical Testing. V. Ramanathan (U. Chicago)

Modelling Atmospheric Transmission and Emission.
J. Drummond (U. Toronto)

Realistic Syntheses of Atmospheric Spectra.
R. Nicholls (York U.)

Potential Effects of Anthropogenic Trace Gas
Emissions on Atmospheric Ozone, Temperature
Structure, and Surface Climate.
R. Vupputuri (AES)

Discussion

ATMOSPHERIC TRANSMISSION MEASUREMENTS

Chairman, P. Merilees (AES)

Transmission Measurements on Mountain Tops.
D. Johnson & G. Stokes (Batelle)

Infrared Transmission Measurements at the Haute
Provence Observatory. P. Marché (U. Reims)

State-of-the-Art in Fourier Transform Infrared
Instrumentation for Atmospheric Measurements.
H. Buijs (BOMEM)

Discussion

Tuesday, 16th September

ATMOSPHERIC EMISSIONS MEASUREMENTS

Chairman, W. Evans (AES)

Trace Constituent Measurements from LIMS and
CLAES. J. Gille (NCAR)

Balloon-Borne Measurements of IR From the Earth's
Surface. D. Murcray (U. Denver)

Ground-Level Monitoring of Longwave Irradiance.
D. Wardle (AES)

Discussion

MEASUREMENTS: INSTRUMENTAL CONSIDERATIONS

Chairman, D. Wardle (AES)

Quality of the Atmosphere for IR Measurements -
Mauna Loa, and the South Pole.
J. DeLuisi (NOAA)

Atmospheric Transmission Measurements using Ground
-Based Fourier Transform Spectroscopy.
M. Coffey (NCAR)

Satellite Measurements of Atmospheric Constituents
by the Pressure Modulation Technique.
H. Roscoe (Oxford U.)

Measurement of Greenhouse Radiation from CFMs.
W.F.J. Evans (AES)

RECEPTION

in honour of
C. L. Mateer

Wednesday, 17th September

**IMPLEMENTING A NETWORK: INSTITUTIONAL
CONSIDERATIONS**

Chairman, W. Evans (AES)

"The Early Detection of Stratosphere Change":
Report on The Workshop, Boulder, Colorado.
J. Margitan (NASA)

**FACILITIES, PLANNED OBSERVATIONS
AND NETWORKS**

Chairman, W. Evans (AES)

The NOAA Plans for a Climate Change Network.
J. DeLuisi (NOAA)

Facilities at the AES for Monitoring Atmospheric
Radiation. D. Wardle (AES)

A Proposal for a RAGS Observatory.
W.F.J. Evans (AES)

Discussion

FINAL PLENARY SESSION

Chairman W.F.J. Evans (AES)

The Final Report
A. Forester (Dartside)

Plenary Discussion

Thursday, 18th September

PREPARATION AND WRITING OF FINAL REPORT

Working sessions through to Friday, 19th September

APPENDIX C: CONTRIBUTORS AND PARTICIPANTS

Dr. Bruce R. Barkstrom
NASA Langley Research Centre
Hampton, Virginia 23665
U.S.A.

(804) 865-2977

Dr. George J. Boer
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4825

Dr. Henry Buijs
BOMEM Inc.
625 Rue Marais
Ville de Vanier, P.Q., G1M 2Y2
Canada

(418) 683-1707

Prof. Robert D. Cess
Laboratory of Atmosphere Research
Department of Mechanical Engineering
State University of New York--Stonybrook
Long Island, New York 11794-2300
U.S.A.

(516) 246-6764

Dr. Alex D. Chisholm
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4816

Dr. Michael Coffey
National Center for Atmospheric Research
P.O. Box 3000
1850 Table Mesa Drive
Boulder, Colorado 80307
U.S.A.

(303) 497-1407

Dr. Roger Daley
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4967

Dr. John DeLuisi

National Oceanographic & Atmospheric Administration
GMCC/ERL, 325 The Broadway
Boulder, Colorado 80302
U.S.A.

(303) 497-6824

Dr. James R. Drummond

Department of Physics
University of Toronto
Toronto, Ontario, M5S 1A7
Canada

(416) 978-4723

Dr. A. Dudhia

Department of Atmospheric Physics
Clarendon Laboratory
Oxford University
Parks Road, Oxford
England

011-44-865-53344

Dr. W.F.J. Evans

Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4835

Dr. Hans Fast

Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4830

Dr. Andrew J. Forester

Dartside Consulting
151 Yonge Blvd.
Toronto, Ontario, M5M 3H3
Canada

(416) 482-8258

Dr. John Gille

National Center for Atmospheric Research
P.O. Box 3000, 1850 Table Mesa Drive
Boulder, Colorado 80307
U.S.A.

(303) 497-1402/1000

Dr. Douglas Johnson

Batelle Pacific Northwest Laboratories
P.O. Box 999
Richland, Washington 99352
U.S.A.

(509) 376-8642

Dr. Virgil G. Kunde
Mail Stop 693.2
NASA - Goddard Space Flight Center
Greenbelt, Maryland 20771
U.S.A.

(301) 286-5693

Dr. Pierre Marché
Département de Physique Moléculaire
Faculté des Sciences
Université de Reims
B.P. 347, 51062
Reims, Cedex
France

2685-2324/2155

Dr. James Margitan
NASA Head Quarters [Code EE]
600 Independence Avenue
Washington, D.C. 20546
U.S.A.

(202) 453-1716

Dr. L.J. Bruce McArthur
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4713

Dr. Philip E. Merilees
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4883

Prof. David Murcay
Department of Physics
University of Denver
2112 East Westley Street
University Park
Denver, Colorado 80208
U.S.A.

(303) 871-2627

Prof. Ralph W. Nicholls
Centre for Research in Experimental Space Science
Petrie Building
York University
4700 Keele Street
Downsview, Ontario, M3J 1P3
Canada

(416) 736-5247

Prof. V. Ramanathan
Department of Geophysics
University of Chicago
Chicago, Illinois 60637
U.S.A.

(312) 962-6194

Dr. Howard Roscoe
Department of Atmospheric Physics
Clarendon Laboratory
Oxford University
Parks Road, Oxford
England

011-44-865-53344

Dr. Gerald Stokes
Batelle Pacific Northwest Laboratories
P.O. Box 999
Richland, Washington 99352
U.S.A.

(509) 375-3816

Dr. R.K.R. Vupputuri
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4820

Dr. David I. Wardle
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H 5T4
Canada

(416) 667-4834

Drs. Barkstrom, Cess, Dudhia and Kunde did not to attend the meeting but made valuable contributions to the report.

APPENDIX D: ABBREVIATIONS AND ACRONYMS

ADN	Automatic Data Network
AES	Atmospheric Environment Service (Canada)
AFGL	Air Force Geophysical Laboratory, U.S.A.
ALPEX	Alpine Experiment
ASA	Automated Shipborne Aerological Program
ATMOS	Atmospheric Trace Molecule Spectroscopy
ATS	Applications Technology Satellite
AVCSR	Airborne Version Conical Scan Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bidirectional Reflectance Distribution Function
CAS	Commission for Atmospheric Sciences, WMO
CCC	Canadian Climate Centre
CCM	Community Climate Model
CDF	Climate Data File
CFC	Chlorinated Fluorocarbons
CFM	Chlorinated Fluoromethanes
CLAIRE	Clear Air Infrared Radiation Experiment
CLAES	Cryogenic Limb Array Etalon Spectrometer
CNRS	Centre Nationale Recherche Scientifique, France
COSPAR	Committee on Space Research
CVF	Circular Variable Filter
DOE	Department of Environment, Canada <u>or</u> Department of Energy, U.S.A.
EC	European Community
ECMWF	European Centre for Medium Range Weather Forecasts
ENSO	El Niño/Southern Oscillation
EOS	Earth Observation Satellite
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
ERL	Environmental Research Laboratory, NOAA
ESA	European Space Agency
ESOC	European Space Operations Center
FAG	Fine Adjustment of Gain
FASINEX	Frontal Air-Sea Interaction Experiment
FGGE	First GARP Global Experiment
FIFE	First ISLSCP Field Experiment
FIRE	First ISCCP Regional Experiment
FOV	Field of View
FTIR	Fourier Transform of Infrared
FTS	Fourier Transform Spectrometer

GAC	Global Area Coverage
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
GISS	Goddard Institute for Space Studies
GMCC	Geophysical Monitoring for Climate Change
GMS	Geostationary Meteorological Satellite
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GOES-NEXT	Next Generation GOES System
HEX-MAX	Humidity Exchange Over the Sea Experiment-Main Experiment
HIRS	High Resolution Infrared Sounder
IAMAP	International Association of Meteorology and Atmospheric Physics
ICRCCM	Intercomparison of Radiation Codes in Climate Models
IEA	International Energy Agency
IGOSS	Integrated Global Ocean Services System
IPS	International Pyrheliometric Scale
IR	Infrared
ISAMS	Improved Stratospheric and Mesospheric Sounder
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land-Surface Climatology Project
JASIN	Joint Air-Sea Interaction Experiment
JSC	Joint Scientific Committee
KPNO	Kitt Peak National Observatory
LBL	Line-by-line
Lidar	Laser Infrared Radar
LIMS	Limb Infrared Monitor of the Stratosphere
LRIR	Limb Radiance Inversion Radiometer
LW	Longwave
METEOSAT	The European Satellite
MIEC	Meteosat Information Extraction Centre, Darmstadt
MILDEX	Mixed Layer Dynamic Experiment
MIZEX	Marginal Ice Zone Experiment
MLO	Mauna Loa Observatory
MLS	Microwave Limb Sounder
MONEX	Monsoon Experiment
MSU	Microwave Sounding Unit

NARC	National Atmospheric Radiation Centre, Canada
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NESDIS	National Earth Satellite, Data and Information Service
NESS	National Earth Satellite Service (now NESDIS)
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory, U.K.
NRC	National Radiation Center
OHP	L'Observatoire de Haute-Provence
PCDS	Pilot Climate Data System
PLDS	Pilot Land Data System
PMR	Pressure Modulated Radiometer
PNL	Battelle, Pacific Northwest Laboratory
PRT	Pt Resistance Thermometers
RAGs	Radiatively Active Gases
rms	root mean square
SAMS	Stratospheric and Mesospheric Sounder
SEFDT	Solar and Earth Flux Data Type
SEMRTS	Solar Energy Meteorological Research and Training Site
SMMR	Scanning Multichannel Microwave Radiometer
SMS	Synchronous Meteorological Satellite
SN (sn)	Signal to Noise Ratio
SPO	South Pole Observatory
SRB	Surface Radiation Budget
SRBC	Surface Radiation Budget Center
SST	Sea-Surface Temperature
STORM	Stormscale Operational and Research Meteorology
STREX	Storm Transfer Region Experiment
SUNY	State University of New York
SW	Shortwave
TIROS	Television and Infrared Operational Satellite operated by NOAA
TOA	Top of the Atmosphere
TOGA	Tropical Ocean and Global Atmosphere
TOMS	Total Ozone Monitoring Spectrometer
TOVS	TIROS Operational Vertical Sounder
UARS	Upper Atmospheric Research Satellite
UNEP	United Nations Environmental Program
UV	Ultraviolet
UWO	University of Western Ontario

VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infrared Spin Scan Radiometer
VUV	Vacuum Ultraviolet
WB	Wide Band
WCP	World Climate Program
WCRP	World Climate Research Program
WG	Working Group
WMO	World Meteorological Organization
WMO-CIMO	WMO Commission for Instruments and Methods of Observation
WOCE	World Ocean Circulation Experiment
WRC	World Radiation Center
WRDC	World Radiation Data Center
WRR	World Radiometric Reference
WWW	World Weather Watch
XBT	Expendable Bathythermograph

Note: This list covers items used in both the report and technical appendices.

APPENDIX E: GLOSSARY

Aerosol

A suspension, in a gaseous medium, of solid particles, liquid particles or solid and liquid particles, having a negligible falling velocity.

Albedo

The ratio of the amount of electromagnetic radiation reflected by a body to the amount incident upon it, commonly expressed as a percentage. The albedo is to be distinguished from reflectivity, which refers to one specific wavelength.

Black Body

An ideal body which absorbs all incident radiation at every wavelength and from all directions while reflecting none and emitting the maximum amount of energy at each wavelength and in all directions for a given temperature.

Calibration

The determination, by measurement or comparison with a standard, of the accuracy of a measuring instrument.

Carbon dioxide, CO₂

A colourless, odorless, tasteless gas which is uniformly mixed throughout the atmosphere at approximately 330 ppmv. It has an emission band at approximately 15 μm .

Characterization

The assessment of the quality of an instrument by its response to variation in its physical environment and signal input, e.g. temperature response, time constant, measurement repeatability, linearity of response.

**Chlorinated
Fluorocarbons, CFCs**

Hydrocarbons such as Freon in which some or all hydrogen atoms have been replaced by chlorine and fluorine atoms. Their emission characteristics make them important RAGs.

**Chlorinated
Fluoromethanes, CFMs**

CFCs consisting of halogenated methane.

Constituents

As used in the report, refers to those gases which directly or indirectly effect the radiative exchanges in the atmosphere e.g., CO_2 , CH_4 , N_2O , etc.

Continuum/Continua

Low level absorption and emission by water vapour across the atmospheric window due to the wings of strong water vapour bands outside the window and possibly weak rotational lines within the window itself.

Flux, Flux Density

The power transferred onto, or across, a unit area of surface from all directions within a hemisphere. In this report the surface is always horizontal. Synonyms: Flux = (spectrally integrated flux) = irradiance = (non-spectral irradiance) with units Wm^{-2} .

Gas Chromatography

A separation technique involving passage of a gaseous moving phase through a column containing a fixed absorbing phase. Used principally as a quantitative analytical technique for volatile compounds.

**General Circulation
Model, GCM**

Complex computer simulations
of the global climate.

Greenhouse effect

Heating effect exerted by the
atmosphere upon the earth
because the atmosphere absorbs
and re-emits infrared radia-
tion. The functional analogy
to a greenhouse is false (see
"Background" section of the
report).

Infrared Radiation, IR

Electromagnetic radiation
whose wavelengths lie in the
range of 0.75 or 0.8 μm to
10000 μm (this is the normal
definition from physics: see
also short- and long wave).

Intensity

The power originating from a
given direction and being
transferred across a unit
surface normal to that
direction. Units $\text{Wm}^{-2} \text{sr}^{-1}$ (=
radiance).

Interferometer

Optical instrument using twin
beam or multi-beam
interference of light to make
measurements with high
spectral resolution.

Irradiance

See "Flux".

Latent Heat

Quantity of heat absorbed or
emitted, without change of
temperature, during a change
of state of a material, units
 Jkg^{-1} .

Lidar

Laser infrared radar: an
instrument in which a laser
generates intense radiation
pulses in beam widths as small
as 30 seconds of arc. The
beam reflections and
scattering effects of clouds,
smog layers and some
atmospheric discontinuities
are measured by radar tech-
niques.

Line-by-Line, LBL

When used in radiation calculations it means computing the radiative properties at each and every line (see "Spectral Line") of the substance involved.

Limb

Circular outer edge of a celestial body. The half with greater altitude is called the upper limb, and the half with the lesser altitude, the lower limb.

Line Profiles

See "Continua".

Longwave Radiation

Terrestrial radiation: that emitted by the earth and the atmosphere in the approximate temperature range of 200-300 K and confined within the wavelengths 3-100 (or >4) μm .

Malkmus Model

An analytical approximation to a spectral absorption band.

Methane, CH_4

A colourless, odorless gas which is lighter than air having strong infrared absorption bands at 3.3, 3.8, and 7.7 μm .

Nadir

The point on the celestial sphere vertically below the observer, or 180 deg. from the zenith.

Nitrous Oxide, N_2O

A colourless, sweet-tasting gas which is slightly soluble in water. It has strong infrared absorption bands at 4.5 and 7.8 μm .

Opacity

Light flux incident upon a medium divided by the light flux transmitted by it.

Optical Depth

A measure of atmospheric opacity. Incident radiation is reduced by e^n as it passes through the atmosphere (e = natural base log; n = optical depth).

Ozone, O_3

An unstable blue gaseous allotrope of oxygen and is a powerful oxidant. It absorbs energy in the 0.1-0.3 and 0.4-0.65 μm bands of the solar spectrum and strongly at 4.7, 9.6, 10.5 and 14.1 μm in the infrared.

Pyranometer

Instrument for measuring solar irradiance.

Pyrgeometer

Instrument for measuring long-wave irradiance.

Radiance

See "Intensity".

Radiant Flux

Rate of transfer of radiant energy, units W.

Radiative Transfer

Transmission of heat by electromagnetic radiation.

Radiometer

Instrument for measuring radiation.

Sensible Heat

Enthalpy, the sum of the internal energy of a system plus the product of the system's volume multiplied by the pressure exerted on the system by its surroundings.

Shortwave Radiation

Solar radiation with a peak intensity at approximately 0.5 μm and confined within the wavelength limits of 0.29 and 4.0 (< 4.0) μm .

Spectral Line	A bright or dark line found in the spectrum of some radiant source. The wavelength location of the line is controlled by the physics of emission (bright line) or absorption (dark line) process.
Spectral Intensity	Radiance per unit wavelength interval. Preferred units $\text{Wm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (= spectral radiance).
Spectral Flux	Flux per unit wavelength interval. Units $\text{Wm}^{-2} \mu\text{m}^{-1}$ (= spectral irradiance).
Spectral Radiance	Synonym for spectral intensity and spectrally resolved radiance.
Spectral Irradiance	Synonym for spectral flux and spectrally resolved irradiance.
Spectrometer	An instrument consisting of (in its simplest form) a slit, collimator lens, prism or grating, objective lens and a photoelectric photometer. Used to measure radiant intensities a various wavelengths.
Stratosphere	Region of the atmosphere extending approximately from 10-20 km up to 50 km in altitude. Temperature increases with height and the radiation balance controls the temperature distribution in this region.

Thermal Inertia

Term expressing the stability of the temperature of some object when subjected to a change in external temperature. Used loosely in this document to describe the slow response of the ocean surface temperature, caused by the large latent heat of water.

Tropopause

The atmospheric boundary between the troposphere and the stratosphere, usually characterized by an abrupt change in the lapse rate. The altitude of the tropopause varies between 15-20 km in the tropics to 10 km in polar regions.

Troposphere

The lower layers of the atmosphere extending from the surface to between 10-20 km. The region is characterized by generally decreasing temperature with altitude and is where clouds and precipitation are usually confined.

Ultraviolet, UV

Radiation of wave length in the range 1-400 nm (0.001-0.4 μm).

Umkehr Effect

Anomalous variation in relative intensity of solar radiation as sun approaches horizon caused by the absorption of some UV wavelengths by ozone. Used to estimate the vertical distribution of ozone.

Window

A region of the spectrum where there is little absorption.

Window Edges

Those regions of the electromagnetic spectrum where absorption/emission characteristics change rapidly with wavelength, especially around 8,13,17 & 19 μm .

Zenith Angle

The between a particular direction and the local vertical.

Note: This glossary to be used both with the report and technical appendices.

CA 1 EP 258 86 172

Canada. A.E.S.

The Status of
Radioactively Active Gases...

RESOURCE CENTRE
INST. FOR ENVIRON'L. STUDIES
UNIVERSITY OF TORONTO



